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### Version of attached file:

Accepted Version

### Peer-review status of attached file:

Peer-reviewed

### Citation for published item:

Hu, Y. and Niu, Y. and Li, J.Y. and Ye, L. and Kong, J.J. and Chen, S. and Zhang, Y. and Zhang, G.R. (2016) 'Petrogenesis and tectonic significance of the late Triassic mafic dikes and felsic volcanic rocks in the East Kunlun Orogenic Belt, Northern Tibet Plateau.', *Lithos.*, 245 . pp. 205-222.

### Further information on publisher's website:

<http://dx.doi.org/10.1016/j.lithos.2015.05.004>

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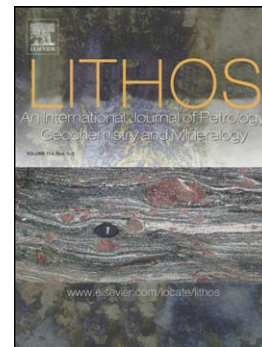
Petrogenesis and tectonic significance of the Late Triassic mafic dikes and felsic volcanic rocks in the East Kunlun Orogenic Belt, Northern Tibet Plateau

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PII: S0024-4937(15)00162-0  
DOI: doi: [10.1016/j.lithos.2015.05.004](https://doi.org/10.1016/j.lithos.2015.05.004)  
Reference: LITHOS 3590

To appear in: *LITHOS*

Received date: 3 March 2015  
Accepted date: 4 May 2015



Please cite this article as: Hu, Yan, Niu, Yaoling, Li, Jiyong, Ye, Lei, Kong, Juanjuan, Chen, Shuo, Zhang, Yu, Zhang, Guorui, Petrogenesis and tectonic significance of the Late Triassic mafic dikes and felsic volcanic rocks in the East Kunlun Orogenic Belt, Northern Tibet Plateau, *LITHOS* (2015), doi: [10.1016/j.lithos.2015.05.004](https://doi.org/10.1016/j.lithos.2015.05.004)

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**Petrogenesis and tectonic significance of the Late Triassic mafic dikes  
and felsic volcanic rocks in the East Kunlun Orogenic Belt, Northern  
Tibet Plateau**

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## Abstract

We present zircon U-Pb ages and geochemical data on the late Triassic mafic dikes (diabase) and felsic volcanic rocks (rhyolite and rhyolitic tuff) in the East Kunlun Orogenic Belt (EKOB). These rocks give a small age window of 228-218 Ma. The mafic dikes represent evolved alkaline basaltic melts intruding ~ 8-9 Myrs older and volumetrically more abundant A-type granite batholith. Their rare earth element (REE) and multi-element patterns similar to those of the present-day ocean island basalts (OIB) except for a weak continental crustal signature (i.e., enrichment of Rb and Pb and weak depletion of Nb, Ta and Ti). Their trace element characteristics together with the high  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.7076- 0.7104), low  $\epsilon_{\text{Nd}(t)}$  (-2.18 to -3.46), low  $\epsilon_{\text{Hf}(t)}$  (-2.85 to -4.59) and variable Pb isotopic ratios are consistent with melts derived from metasomatized subcontinental lithospheric mantle with crustal contamination. The felsic volcanic rocks are characterized by high LREE/HREE (e.g.,  $[\text{La}/\text{Yb}]_{\text{N}}$  of 5.71-17.00) with a negative Eu anomaly and strong depletion in Sr and P, resembling the model upper continental crust (UCC). Given the high  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.7213-0.7550) and less negative  $\epsilon_{\text{Nd}(t)}$  (-3.83 to -5.09) and  $\epsilon_{\text{Hf}(t)}$  (-3.06 to -3.83) than the UCC plus the overlapping isotopes with the mafic dikes and high Nb-Ta rhyolites, the felsic volcanic rocks are best interpreted as resulting from melting-induced mixing with 45-50% crustal materials and 50-55% mantle-derived mafic melts probably parental to the mafic dikes. Such mantle-derived melts underplated and intruded the deep crust as juvenile crustal materials. Partial melting of such juvenile crust produced felsic melts parental to the felsic volcanic rocks in the EKOB. We hypothesize that the late

Triassic mafic dikes and felsic volcanic rocks are associated with post-collisional extension and related orogenic collapse. Such processes are probably significant in causing asthenospheric upwelling, decompression melting, induced melting of the prior metasomatized mantle lithosphere and the existing crust. This work represents our ongoing effort in understanding the origin of the juvenile crust and continental crustal accretion through magmatism in the broad context of orogenesis from seafloor subduction to continental collision and to post-collisional processes.

**Keywords:** alkaline mafic dikes; felsic volcanic rocks; subcontinental lithospheric mantle; crustal anatexis; post collision; East Kunlun Orogenic Belt

## 1. Introduction

The Late Triassic volcanic rocks are widespread along the East Kunlun Orogenic Belt (EKOB), stratigraphically concentrated in two formations: the Elashan Formation ( $T_{3e}$ ) and the Babaoshan Formation ( $T_{3b}$ ) (Fig. 1c). The Elashan Formation distributes discontinuously along the entire EKOB with lithologies including abundant basalt, trachyandesite, trachyte, andesite, rhyolite and pyroclastic rocks. Additionally, in its western section there also exist abundant diabasic dikes of alkaline composition ( $218.1 \pm 2.5$  Ma) in the volumetrically more abundant A-type granitoids ( $227.0 \pm 3.3$  Ma) (Hu et al., in preparation) extending W-E for about 50 kilometers (Fig. 2a, b, c). Significant volumes of coeval felsic volcanic rocks ( $227.5 \pm 1.5$  Ma to  $219.5 \pm 1.9$  Ma) crop out toward its eastern section (Fig. 2d, e). Mafic dikes of mantle

origin provide key information on their petrogenesis in particular and geodynamic processes in general. They can be derived from asthenospheric mantle associated with subduction, rift and mantle plume activities (Buchan et al., 1998; Chen et al., 2011; Goldberg, 2010; Hoek and Seitz, 1995; Srivastava, 2011; Stepanova and Stepanov, 2010), but they can also result from melting of subcontinental lithospheric mantle (SCLM) in response to surface extension and lithosphere thinning (Liu et al., 2012; Williams et al., 2001). The origin of felsic volcanic rocks coeval with the alkaline mafic rocks is commonly interpreted as resulting from (1) advanced extent of fractional crystallization of mantle-derived mafic magmas directly (Shao et al., 2015; Tian et al., 2010; Turner et al., 1992), (2) partial melting of crust triggered by heating of mantle-derived mafic magmas (Christiansen et al., 1983; Huppert and Sparks, 1988; Ratajeski et al., 2001; Takanashi et al., 2011), and (3) hybridization of crustal melts with mantle-derived mafic melts (Ding et al., 2011; Yang et al., 2008).

The EKOB is one of the major tectono-magmatic belts on the Greater Tibetan Plateau. It records a long history of magmatism and tectonic evolution beginning in the Early Paleozoic and continuing into the Cenozoic (Ding et al., 2011; Mo et al., 2007; Xiong et al., 2013; Yang et al., 1996). The paleo-ocean recorded by the EKOB between Laurasia and Gondwana has been regarded as having undergone multi-cycle tectonic evolution with opening and closing of Pre-Prototethys, Prototethys and Paleotethys oceans (Yin and Zhang, 1997). The latest opening-closing cycle recorded by the EKOB is termed the A'nyemaqen Ocean (Jiang et al., 1992; Mo et al., 2007), which is thought to be the north branch of the Paleotethys Ocean (Jiang et al., 1992;

Yang et al., 1996). The timing of the A'nyemaqen seafloor subducting, closing and continental collision remains controversial. Many consider that the seafloor subduction occurred during the Late Permian to Middle Triassic (Harris et al., 1988) with continental collision in the Late Triassic (Guo et al., 1998; Liu et al., 1984; Luo et al., 2002; Mo et al., 2007), but others differ. For example, Pan et al. (2012) proposed that the EKOB records a syn-collisional setting in the Early to Middle Triassic and a post-collisional setting in the Late Triassic. Yang et al. (2009) argued that the A'nyemaqen Ocean opened as early as the Late Carboniferous (308Ma) and was closed probably during the Early Triassic, as marked by island arc volcanic rocks of the Late Permian age (260Ma), back arc basin basalts in the Early-Middle Triassic and the post-collisional volcanic rocks in the Late Triassic. Recently, Xia et al. (2014) proposed, using new data and data in the literatures, that seafloor subduction started at ~ 260Ma (Late Permian), lasting for 20Myrs before continental collision from 240 to 232Ma (Middle Triassic).

Previous studies have been focused on the volcanic rocks from the eastern section of the EKOB (Ding et al., 2011; Li et al., 2013a; Liu et al., 2014a; Xiong et al., 2014a; Yang et al., 2009; Zhu et al., 2006). In this paper, we report the coeval mafic dikes together with rhyolitic volcanic rocks along the entire EKOB. More importantly, to reveal the petrogenesis of the late Triassic mafic dikes and felsic volcanic rocks and the regional tectonic setting of the EKOB in the Late Triassic, we present new high-quality zircon U-Pb ages for both mafic dikes and felsic volcanic rocks from each section of the EKOB and their bulk-rock major element, trace element and

Sr-Nd-Pb-Hf isotopic compositions. Using these data, we discuss the petrogenesis of these sub-volcanic and volcanic rocks in the context of the EKOB evolution.

## 2. Geological setting and samples

The Tibetan Plateau is a huge composite terrane amalgamated through multiple continental collision events expressed by progressively younger sutures from northeast in the early Paleozoic to southwest in the Cenozoic (Harris et al., 1988; Niu et al., 2013). The East Kunlun-Qaidam terrane is constrained between the south Qilian suture and Anyemaqen-Kunlun-Muttagh suture, south of which is referred to as the Kunlun batholith dominated by a broad Early Paleozoic arc and a narrower Late Permian to Triassic arc (Yin and Harrison, 2000) (Fig. 1a). The EKOB is bounded by the Qaidam Basin to the north and Hoh Xil-Songpan-Ganze Basin to the south, which can be divided into three zones: northern (Qimantagh folded zone), middle (granite zone) and southern zones by major faults (i.e., South Kunlun Fault and Central Kunlun Fault) (Fig. 1b; Jiang et al., 1992). Particularly, the northern and middle zones show abundant magmatism (Fig. 1b and c; Yuan et al., 2000).

The continental crust basement of the main magmatism zone of the EKOB is represented by the Paleo- and Mesoproterozoic Jinshuikou Group comprising the lower Baishahe and upper Xiaomiao formations. The lower Baishahe Formation consists of marbles, gneisses, migmatites and amphibolites. The upper Xiaomiao Formation comprises marbles, gneisses, greenschists and quartzites (Jiang et al., 1992; Liu et al., 2014a; Mo et al., 2007; Ren et al., 2010; Xiong et al., 2014a). The EKOB is



characterized by abundant magmatism manifested by the widespread intrusive and volcanic rocks, especially the granitoids and some ophiolitic remnants representing long-lasing magmatic activities from the Proterozoic to the late Mesozoic, which are principally distributed north of the Central Kunlun Fault (Fig. 1; Mo et al., 2007).

The late Triassic mafic dikes and felsic volcanic rocks in the EKOB are all fresh and representative samples collected from the Elashan Formation, including diabases, rhyolitic tuffs and rhyolite porphyries. The mafic dikes intruding the ~ 8-9 Myrs older A-type granite batholith (see below) are best exposed and sampled in the Yeniugou area (“YNG” in Fig. 1c; Fig. 2a; Table 1). The dikes are mostly aphyric (< 5% crystals) with minor plagioclase phenocrysts. The groundmass, with a holocrystalline/diabasic texture, is made up of quench microlites of plagioclase, pyroxene, olivine and opaques (Fig. 2c). The rhyolitic tuffs mainly crop out in the Tufangzi area (“QMX” in Fig. 1c; Table 1), containing glass shards (~60%), crystal clasts of quartz (with melt corrosion/absorption features), plagioclase and biotite (~25% in total) and rhyolite fragments (~15%) (Fig. 2d). The rhyolite porphyry is well exposed and sampled in the Reshui and Yingde’er areas closing to Dulan County (“RSX” and “YDE” in Fig. 1c; Table 1). The phenocrysts are mostly quartz (with melt corrosion shapes), and minor feldspar and biotite (~15% in total) in the glassy groundmass (Fig. 2e).

### 3. Sample preparation and analytical methods

Twenty-seven fresh samples were analyzed for major and trace elements and eleven of them were selected for Sr, Nd, Pb and Hf isotopic analyses (Pb isotopes

done only for the mafic dikes). Three representative samples were chosen for zircon U-Pb dating.

### *3.1. Zircon U-Pb dating*

Zircon crystals were selected using techniques of heavy liquid and magnetic separation, followed by hand-picking before mounted in epoxy resin and polished down to ~ half thickness (Song et al., 2002; Xiu et al., 2001). Cathodoluminescence (CL) images were obtained using a CL spectrometer (Gatan MonoCL4+) equipped on a FEI Quanta 450 FEG scanning electron microscope (SEM) at China University of Geosciences, Wuhan (CUGW) to reveal their internal structures and to choose spots for U-Pb analysis. The working condition is 0.8-1Kv for Gatan MonoCL4+ and 10Kv for SEM.

Zircon U-Pb dating and trace element analysis were completed synchronously using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at CUGW. Detailed operation conditions for laser ablation and ICP-MS analyses are given in Liu et al. (2010a). The spot diameter is 32  $\mu\text{m}$ . Data were processed using ICPMSDataCal (Liu et al., 2010a; Liu et al., 2010b). Concordia diagrams and weighted mean calculations were done using Isoplot/Ex\_version 3.0 (Ludwig, 2003).

### *3.2. Geochemistry*

Pen and saw marks on all samples were removed in the clean laboratory of the Langfang Institute of Regional Geology and Mineral Investigation, China. Samples

that had obvious phenocrysts were reduced to 0.5-2mm size chips for hand picking under a binocular microscope to select “melt” compositions (i.e., glass shards and fine-grained aphyric portions of the ground mass) followed by ultrasonic cleaning in Milli-Q water, drying and grinding in agate mortars. Aphyric samples with no phenocrysts were reduced to 5-8mm size chips, cleaned and ground similarly in an agate mill. All the sample powders were ensured to have grain size smaller than 200 mesh under thoroughly clean conditions at Lanzhou University.

### *3.2.1. Major and trace elements*

Major element analysis was done using a Leeman Prodigy inductively coupled plasma-optical emission spectroscopy (ICP-OES) system with high dispersion Echelle optics at China University of Geosciences, Beijing (CUGB). About 35 mg powder of each sample was thoroughly dissolved in the mixture of equal  $\text{HNO}_3$  and HF in a Teflon bomb, diluted into 5%  $\text{HNO}_3$  solution, and analyzed using an Agilent-7500a inductively coupled plasma mass spectrometry (ICP-MS) at CUGB for trace elements. Sample digestion and analytical details are given by Song et al. (2010).

### *3.2.2. Sr-Nd-Pb-Hf isotopes*

Samples YNG12-03, YNG12-05, QMX12-01, QMX12-08, QMX12-11, RSX12-48 and YDE12-02 were chosen for whole-rock Sr-Nd-Hf isotopic analysis at CUGW. Hf isotopic analysis for samples DL09-01 and DL09-03 (from Ding et al., 2011) was also done at CUGW. About 100 mg rock powder was digested in the

mixture of  $\text{HNO}_3$ +HF in Teflon bombs in a clean oven at about 190°C for a week. The chemical separation was done following the procedure by Yang et al. (2010). The Sr, Nd isotopic analysis was done on a Thermo Finnigan Triton Ti Thermal Ionization Mass Spectrometer (TIMS), and Hf isotopic analysis was done using a Thermo Neptune Plus Multi-Collector Inductively Coupled Plasma Mass Spectrometer (MC-ICP-MS). The Pb isotopic analysis for samples YNG12-03, YNG12-05, YNG12-01 and YNG12-08 was done in the Radiogenic Isotope Facility at The University of Queensland (UQ), Australia (see below).

For samples YNG12-01 and YNG12-08, the whole-rock Sr, Nd, Pb and Hf isotopic analysis was done at UQ. About 200 mg sample powder was digested in the mixture of double-distilled concentrate  $\text{HNO}_3$  and HF, and dried down on a hot plate at 80 °C. After converting any fluoride to nitrate, the dried residue was dissolved with 3ml 2N  $\text{HNO}_3$ . 1.5ml was loaded onto a stack of Sr-spec, TRU-spec, and Ln-spec resin columns to separate Sr, Pb and Nd from matrix using a modified procedure following Deniel and Pin (2001), Míková and Denková (2007) and Pin and Zalduegui (1997) (also see Guo et al., 2014); another 1.5ml was used to pass through a Ln-spec resin column for Hf separation following Yang et al. (2010). The Sr, Nd, Pb and Hf isotopic ratios were measured on a Nu Plasma HR MC-ICP-MS.

#### **4. Analytical data**

##### *4.1. Zircon U-Pb ages*

Representative CL images of analyzed zircons and corresponding concordia

diagrams are shown in Fig. 3 and Fig. 4 respectively. The age data are given in Table 2. Zircons from the mafic dikes are pale green and those from the felsic volcanic rocks are pale brown and dark red. They yield weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  ages ranging from 228 to 218 Ma, similar to the age of the A-type granite (see below), which suggests that they are coeval within analytical error (Fig. 4), although the mafic dikes with chilled margins (Fig. 2b) are ~ 8-9 Myrs younger than the host A-type granites (see below).

Zircons from dike sample YNG12-03 are euhedral columnar crystals (80-150  $\mu\text{m}$  long) with aspect ratios of ~ 1.5:1-2:1 (some fragments could be fractured/produced during separation, Corfu et al., 2003) (Fig. 3a). In CL images, they show lower homogeneous luminescence and less obvious regular oscillatory zoning than those in rhyolitic rocks (Fig. 3). The LA-ICP-MS U-Pb analysis gives variable Th (242-2508 ppm) and U (658-7565 ppm) concentrations with Th/U ratios of 0.25-0.67 (Table 2), which are consistent with their being of magmatic origin (Belousova et al., 2002; Hoskin and Schaltegger, 2003). Thus the youngest U-Pb age group of the zircons is probably the crystallization age of the rock. Twelve zircons from this sample plot in-group on the concordia and yield a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $218.1 \pm 2.5$  Ma (MSWD =2.9) (Fig. 4a). This age is taken to represent the extrusive age of the mafic dikes. Zircons from the host A-type granite yield a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $227.0 \pm 3.3$  Ma (MSWD =3.4) (Hu et al., in preparation), i.e., the host A-type granite emplaced ~ 8-9 Myrs prior to the dike intrusion, probably different products of a generally the same thermal event.

Zircons from rhyolitic tuff sample QMX12-01 are dark red, euhedral columnar crystals (80-250  $\mu\text{m}$  long) with aspect ratios of  $\sim 1:1-3:1$ . Their CL images display high homogeneous luminescence and strong oscillatory zoning (Fig. 3b). They have varying Th (185-580 ppm) and U (406-1040 ppm) concentrations with Th/U ratios of 0.44-0.66, consistent with the zircons being of magmatic origin (Table 2; Belousova et al., 2002; Hoskin and Schaltegger, 2003). Twenty-two zircons form a tight cluster with a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $219.5 \pm 1.9$  Ma (MSWD =2.5) (Fig. 4b), which is considered as approximating the extrusive age of the rhyolitic tuff representing the felsic volcanism of the EKOB (Note: zircons crystallized in magma chambers prior to eruption).

Rhyolite porphyry sample RSX12-48 was collected from the Reshui area in the east section of the EKOB southeast to Dulan County (Fig. 1). Zircons from this sample are dark red and euhedral columnar crystals (90-250  $\mu\text{m}$  long) with aspect ratios of  $\sim 1:1-3.5:1$  except for some presenting imperfect crystals in CL images. They have lower luminescence (compared with QMX12-01) and obvious oscillatory zoning (Fig. 3c). Zircons from RSX12-48 have variable Th (214-3615 ppm) and U (275-7463 ppm) contents with Th/U ratios of 0.34-0.81 which confirm their magmatic origin (Table 2; Belousova et al., 2002; Hoskin and Schaltegger, 2003). Twelve analyses form a cluster close to the concordia with a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $227.5 \pm 1.5$  Ma (MSWD =0.48) (Fig. 4c). We interpret this as approximating the extrusive age of the rhyolite porphyry from the EKOB.

#### 4.2 Major elements

Whole-rock major and trace element analyses are given in Table 3. The late Triassic mafic dikes and felsic volcanic rocks from the EKOB plot in the fields of basaltic trachyandesite, basaltic andesite, trachyte, trachyte-rhyolite and rhyolite on the total alkali-silica (TAS) diagram (Fig. 5a; Le Bas et al., 1986). In addition, the mafic rocks mainly plot in the alkaline field whereas the felsic volcanic rocks mostly plot in subalkaline division (Irvine and Baragar, 1971).

The mafic rocks represent variably evolved melts characterized by moderate silica (50.35-56.44 wt.%), high  $\text{Al}_2\text{O}_3$  (16.64-17.76 wt.%) and low  $\text{Mg}^\#$  (0.47-0.54) ( $\text{Mg}^\# = \text{molar Mg}/[\text{Mg}+\text{Fe}^{2+}]$ ). They have varying alkaline ( $\text{Na}_2\text{O}+\text{K}_2\text{O}$ ) contents (3.68-7.11 wt.%) and plot in high-K calc-alkaline and shoshonite fields ( $\text{K}_2\text{O} = 1.22\text{-}2.69$  wt.%) (Fig. 5b; Rickwood, 1989). The felsic volcanic rocks have higher silica (66.23-76.02 wt.%) and alkaline ( $\text{Na}_2\text{O}+\text{K}_2\text{O}$ ) (6.70-9.35 wt.%), lower  $\text{MgO}$  (0.11-1.24 wt.%) and  $\text{Al}_2\text{O}_3$  (12.81-15.95 wt.%) as expected. They are mainly in the high-K calc-alkaline series with two samples belonging to calc-alkaline series and three in shoshonite series ( $\text{K}_2\text{O} = 2.74\text{-}5.70$  wt.%) (Fig. 5b; Rickwood, 1989). In  $\text{SiO}_2$  variation diagrams, major element oxides show expected first-order trends except for  $\text{Na}_2\text{O}$ , although they are unlikely related by liquid lines of descent (LLDs) given the differences of these samples in time and space (Fig. 6).

#### 4.3 Trace elements

In the chondrite normalized rare earth element (REE) diagram, the mafic rocks

are enriched in light REEs with very high  $(\text{La/Yb})_N$  (13.22-17.41) and a weak negative Eu anomaly ( $\text{Eu}/\text{Eu}^* = 0.81\text{-}0.97$ ) (Table 3; Fig. 7a). In primitive mantle normalized multi-element diagram (Fig. 7b), they display moderate enrichment in Rb and Pb and weak depletion in Nb, Ta and Ti.

Felsic volcanic rocks show enrichment in LREEs relative to HREEs with  $(\text{La/Yb})_N$  of 5.71-17.00. In the chondrite normalized REE pattern diagram, they show significant negative Eu anomalies ( $\text{Eu}/\text{Eu}^* = 0.12\text{-}0.73$ ) (Table 3; Fig. 7c). Compared with the upper continental crust, the felsic rocks are strongly depleted in Sr and P (Fig. 7d). The large Eu and Sr depletion is consistent with significant plagioclase crystallization as shown petrographically (see Niu and O'Hara, 2009; Fig. 2) during magma evolution from their respective parental melts although varying extent of crustal melting with plagioclase present as a residual phase can also give similar patterns.

#### 4.4 Whole rock Sr-Nd-Pb-Hf isotopes

The isotopic analyses are given in Table 4-6. The initial isotopic ratios are calculated using zircon U-Pb ages of representative samples of this study (see above).

The mafic dikes have present-day  $^{87}\text{Sr}/^{86}\text{Sr}$  of 0.7076-0.7104 (Initial  $^{87}\text{Sr}/^{86}\text{Sr}$  [ $I_{\text{Sr}}$ ] = 0.7070 to 0.7086), giving a positive correlation with  $\text{SiO}_2$  (Fig. 8c). They display slightly enriched Nd and Hf isotopic compositions ( $\epsilon_{\text{Nd}(t)} = -2.18$  to  $-3.46$ ,  $\epsilon_{\text{Hf}(t)} = -2.85$  to  $-4.59$ ), showing an inverse trend between  $\epsilon_{\text{Nd}(t)}$  and  $\text{SiO}_2$  (Fig. 8d). The  $^{206}\text{Pb}/^{204}\text{Pb}$ ,  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{208}\text{Pb}/^{204}\text{Pb}$  ratios of the mafic dikes are 18.789-18.850, 15.644-15.651



and 38.777-38.841, respectively, which may suggest an enriched mantle source of the mafic dikes (see below).

The felsic volcanic rocks have overlapping Nd and Hf isotopes with the mafic dikes ( $\epsilon_{\text{Nd}(t)} = -3.83$  to  $-5.09$  and  $\epsilon_{\text{Hf}(t)} = -3.06$  to  $-3.83$ ) (also see Fig. 9b). However, the present-day  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the felsic rocks are variably high (0.7213 to 0.7550) with  $I_{\text{Sr}} = 0.7083$ -0.7097 (Figs. 8c, 9d) because of the very high Rb/Sr ratios and the strong Sr depletion (see Fig. 7; Table 4).

## 5. Discussion

### 5.1. Petrogenesis of the mafic dikes

#### 5.1.1 Crustal contamination

The mafic dikes have evolved alkaline basaltic composition (Fig. 5). Their trace element systematics are indicative of crustal contamination with elevated abundances of Rb, U and Pb and depletion in Nb, Ta and Ti (Fig. 7; Niu and O'Hara, 2009; Rudnick and Gao, 2003). Also, upper continental crust is characterized by high  $^{87}\text{Sr}/^{86}\text{Sr}$  and low  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios (Liu et al., 2004). Therefore, continental crust derived melts are expected to have lower Nb/Th, Ta/U,  $\epsilon_{\text{Nd}(t)}$  and higher  $^{87}\text{Sr}/^{86}\text{Sr}$  than mantle-derived melts (Fig. 8; Goldstein and Jacobsen, 1988; Rudnick and Gao, 2003). Given the relative incompatibility of  $D_{\text{Nb}} \approx D_{\text{Th}} < D_{\text{Ta}} \approx D_{\text{U}}$  during basaltic magmatism (Niu and Batiza, 1997; Niu and O'Hara, 2009), Nb/Th and Ta/U ratios will remain constant during magmatism and their variation, if any, in samples would be inherited from the source rocks or source histories. If such mafic magmas were

contaminated by the crust, the Nb/Th, Ta/U and  $\epsilon_{\text{Nd}(t)}$  would decrease whereas  $^{87}\text{Sr}/^{86}\text{Sr}$  would increase with increasing  $\text{SiO}_2$ . Indeed, the mafic dikes show inverse correlations of Nb/Th, Ta/U and  $\epsilon_{\text{Nd}(t)}$  with  $\text{SiO}_2$  (Fig. 8a, b and d), and a positive correlation of  $^{87}\text{Sr}/^{86}\text{Sr}$  with  $\text{SiO}_2$  (Fig. 8c). This is also clear in Ta\*-Nb\* space (Fig. 10), with  $\text{Nb}^* < 1$  and  $\text{Ta}^* < 1$ , trending towards continental crust composition as obvious in Fig. 7b. Therefore, the effect of continental crust contamination should be considered when discussing the petrogenesis and sources of the melts parental to the mafic dikes (see below).

#### 5.1.2 Source of the mafic dikes

Compared with common basaltic rocks, the mafic dikes have relatively high  $\text{SiO}_2$  (50.35-56.44 wt.%), but low MgO (3.54-5.34 wt.%), Cr (30.18-95.02 ppm), Ni (14.02-42.78 ppm) and  $\text{Mg}^\#$  (0.47-0.54), indicative of their highly evolved nature from their mantle-derived parental melts through fractional crystallization dominated by olivine and clinopyroxene with, to some extent, crustal contamination (see above). Plagioclase fractionation is insignificant with an apparently weak negative Eu anomaly (Fig. 7a; Table 3).

In general, most basalts are evolved from asthenosphere-derived primitive melts. The asthenosphere is in general depleted in incompatible elements or depleted mantle (DM), but it is variably heterogeneous which can be variably enriched on all scales or enriched mantle (EM). Mid-ocean ridge basalts (MORB) are widely accepted as derived from the DM with depleted incompatible elements and depleted radiogenic

isotopic signatures interpreted to have resulted from continental crust extraction in Earth's early history (Gast, 1968; Niu and O'Hara, 2009). In comparison, the EM is complementarily enriched in incompatible elements and can generate magmas in diverse tectonic settings including plate boundaries and interiors (Anderson, 1981). The EM has variably high  $^{87}\text{Sr}/^{86}\text{Sr}$ , low  $^{143}\text{Nd}/^{144}\text{Nd}$  and high  $^{207}\text{Pb}/^{204}\text{Pb}$ ,  $^{208}\text{Pb}/^{204}\text{Pb}$  at a given  $^{206}\text{Pb}/^{204}\text{Pb}$  (Rollinson, 1993). Sun and McDonough (1989) suggest that the EM is characterized by  $^{87}\text{Sr}/^{86}\text{Sr} \geq 0.7040$ ,  $^{206}\text{Pb}/^{204}\text{Pb} < 18.6$  for EMI and 18.6-19.7 for EMII. Relatively high  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.7076-0.7104),  $^{206}\text{Pb}/^{204}\text{Pb}$  (18.8-18.9) and low  $\epsilon_{\text{Nd}(t)}$  (-2.18 to -3.46) for the mafic dikes are consistent with their derivation from an EM source. Indeed, the Sr-Nd-Hf-Pb isotope (Figs. 8, 9), major element (Figs. 5, 6) and trace element (Fig. 7) compositions indicate that the primitive magmas parental to these mafic dikes are alkaline basalts derived from mantle sources enriched in incompatible elements and likely more enriched than OIB sources (Fig. 7). While the elevated abundances of Rb, U and Pb and relative depletion in Nb, Ta and Ti of these mafic dikes may have been affected by crustal contamination (see above), it is likely that much of these as well as the overall incompatible element enriched signatures may have largely inherited from enriched sources. With the exception of subduction-zone magmatism, melting of asthenospheric mantle will not produce melts with apparent Nb-Ta-Ti depletion, yet subduction-zone magmatism will produce melts with significantly more depleted Nb-Ta-Ti. However, melting of SCLM metasomatized in a mantle wedge environment (with terrestrial sediment input) can produce alkaline basalts parental to the mafic dikes (Huang et al., 2010; Zhao et al.,

2009). Indeed, this interpretation is consistent with the isotopic compositions of these mafic dikes falling with those of SCLM (e.g.,  $^{87}\text{Sr}/^{86}\text{Sr}$  of 0.7035-0.7100 and  $\epsilon_{\text{Nd}}$  of +12 to -7; McDonough et al., 1985). Fig. 9a shows that on the Th/Nb-La/Nb plot (Plank, 2005), most mafic dikes have similar Th/Nb and La/Nb to OIB with a weak arc basaltic signature (i.e., low Nb, hence relatively high Th/Nb and La/Nb), which is in fact consistent with crustal assimilation (see above) or melting of metasomatized mantle lithosphere with sediment input (see above). All these together with the enriched Hf and Nd isotopes (Fig. 9b) manifest that the source of the mafic dikes is similar to that of OIB of metasomatic enrichment origin (Niu, 2008; Niu and O'Hara, 2003; Niu et al., 2002; Niu et al., 2012; Pilet et al., 2008). However, the weak arc-like or continental crust signature (e.g., Nb-Ta-Ti depletion) is consistent with the metasomatism taking place in the mantle wedge setting (Donnelly et al., 2004).

If the continental collision for the EKOB indeed ended in the Early Triassic (Yang et al., 2009), then the EKOB (sub-) volcanism would be considered as taking place in an intra-plate setting. It is yet unknown if such intra-plate magmatism was related to any sort of mantle plumes or post-collisional extension or orogenic collapse because conceptually all of these alternatives could cause asthenospheric upwelling, decompression melting, induced melting of prior metasomatized mantle lithosphere (e.g., during subduction episode) or even crustal melting (see below). We consider that it is immature at present to make any solid conclusion on this matter without further research. However, we can suggest that post-collisional extension (and related orogenic collapse) is a reasonable hypothesis to be tested in future studies. This is

because post-collisional magmatism can continue ~ 55 Myrs after continental collision, e.g., in southern Tibet (see Liu et al., 2014b; Zhao et al., 2009).

## 5.2. Origin of the felsic volcanic rocks

Given the differences of mafic dike and felsic volcanic rock samples in time and space, they are unlikely related to one another by fractional crystallization although the major element oxides show expected first-order trends except for Na<sub>2</sub>O in SiO<sub>2</sub> variation diagrams (Fig. 6). Distinct isotopic compositions and different ratios of similarly incompatible elements (e.g. Nb/Th and Ta/U) of mafic and felsic rocks (Fig. 8) also preclude their genetic link through fractional crystallization.

The strongly fractionated LREE/HREE ratios ( $[La/Yb]_N = 5.71$  to  $17.00$ ) imply a partial-melting origin for the felsic volcanic rocks. Magmas derived by anatexis of continental crust typically have high  $^{87}Sr/^{86}Sr$  ratios and low Sr contents (Hawkesworth and Vollmer, 1979). They preserve or increase the LILE/HFSE ratios of Rb/Nb and Rb/Zr during crustal anatexis, as Rb is more incompatible than Nb and Zr (Peccerillo et al., 2003). High  $^{87}Sr/^{86}Sr$  ( $0.7213$  to  $0.7550$ ), low Sr contents ( $25.46$  to  $295$  ppm), and positive trends in Fig. 11a and b of the felsic volcanic rocks are all in favor of the crustal origin. In addition, during magma evolution from their respective parental melts, plagioclase is a dominated crystallization phase, and with increasing extent of fractional crystallization SiO<sub>2</sub> increases while Sr and Eu (hence  $Sr/Sr^*$  and  $Eu/Eu^*$ ) decrease in the melt as a result, leading to the negative correlations of  $Sr/Sr^*$  and  $Eu/Eu^*$  with SiO<sub>2</sub> (Figs. 11c, d). This interpretation is also consistent

with the  $\text{SiO}_2$  co-variations with all other major elements (Fig. 6). It should be noted that the reverse of these correlations could also result from plagioclase presence as a residual phase during crustal melting. That is, one can prefer one possibility over another, but the interpretation is actually not unique, and both may actually be important.

In order to distinguish in which continental crust level the melts parental to the felsic volcanic rocks generated, the felsic rocks are compared with average composition of the upper (UCC) and lower (LCC) continental crust in Figure 7. They present almost identical patterns with the UCC except for Eu, Sr and P (Fig. 7c, d), which are more depleted because of their more evolved nature with greater extent of plagioclase and apatite crystallization/removal. Upper crustal Zr/Y (8.3) and Sm/Nd (0.18) ( $\text{Zr/Y} = 9.19$ ,  $\text{Sm/Nd} = 0.174$  [UCC] vs.  $\text{Zr/Y} = 4.25$ ,  $\text{Sm/Nd} = 0.255$  [LCC]; Rudnick and Gao, 2003) further favour the genetic connection of the felsic volcanic rocks with the UCC. More importantly, the felsic volcanic rocks show  $\text{Ta}^*$  and  $\text{Nb}^*$  closely resemble those of the UCC, but significantly differ from the LCC (Fig. 10). This is because the lower crustal granulite rocks are depleted in U (relative to Ta and Th) and thus have the highest Th/U of 6.0 (vs. 3.9 [upper crust] and 4.3 [bulk crust]) and Ta/U of 3.0 (vs. 0.33 [upper crust] and 0.54 [bulk crust]) (Rudnick and Gao, 2003). This could suggest the upper crustal melting, but melting and melt segregation may actually take place in the lower crust with the melt emplaced in the upper crust undergoing varying extent of fractionation towards the observed felsic volcanic rocks. Felsic granulites in the LCC, which have been proved to be widespread and share

larger proportions (vs. mafic granulites) (Hans Wedepohl, 1995; Liu et al., 1996; Liu et al., 2001), may make main contributions to the felsic volcanic rocks at the deeper level when mafic magmas underplated from below. However, it is worth noting that the felsic volcanic rocks are isotopically more depleted than the UCC with higher  $\epsilon_{\text{Nd}(t)}$  (-3.84 to -5.09) and lower  $I_{\text{Sr}}$  (0.7083-0.7097) (Figs. 8d, 9d) while displaying overlapping Nd-Hf isotopic compositions with the high Nb-Ta rhyolites and the mantle-derived mafic dikes (Fig. 8d and Fig. 9b, d; Ding et al., 2011). These observations require somewhat mixed sources to account for the petrogenesis of the felsic volcanic rocks. Apparently, mantle-derived alkaline basaltic melts parental to the mafic dikes must have been involved. Figure 9d plots various rocks from the EKOB in  $\epsilon_{\text{Nd}(t)}$  vs.  $I_{\text{Sr}}$  space. The late Triassic mafic dikes and felsic volcanic rocks fall in the range of intrusive igneous rocks derived from lithospheric mantle with input of crustal materials (see above).

With all the conceivable possibilities considered, we propose that the late Triassic mafic dikes represent melts evolved from alkaline basalts of metasomatized lithospheric mantle origin. Such mantle derived melts underplate and intrude the deep crust as juvenile crustal material. Partial melting of such juvenile crustal material produced felsic melts parental to the felsic volcanic rocks in the EKOB. That is, many of the original materials were derived directly (alkaline melts parental to the mafic dikes) or indirectly (felsic volcanic rocks) from the mantle in no distant past with varying extent of prior crustal contributions (i.e., subducted terrestrial sediments for metasomatizing the mantle lithosphere, deep crustal melting/assimilation and upper

crustal contamination etc.). In Figure 12, we attempt to estimate the relative proportions of crust and mantle contributions to the petrogenesis of mafic dikes and felsic volcanic rocks in terms of Sr and Nd isotopes. We choose two end members: (1) OIB-like basalts from the Zhiduo and Zaduo areas as representing the contemporary Paleo-Tethyan mantle component (Ma et al., 2007); (2) Jinshuikou cordierite granites from northeastern margin of the Tibetan plateau as representing the upper continental crust (Ba et al., 2012). The calculations show that isotopically, the felsic volcanic rocks represent mixing (melting and melt hybridization) of 45-50% crustal materials and 50-55% mantle-derived alkaline mafic melts (Fig. 12). If the latter is parental to the mafic dikes, then these dikes represent hybridization of ~ 65% of mantle materials and ~ 35% mature crustal materials.

The above is conceptually important for understanding the origin of the juvenile crust and continental crustal accretion through magmatism in the broad context of the orogenesis from seafloor subduction to continental collision and to post-collisional processes (see Niu et al., 2013 for review).

### *5.3. Tectonic significance*

The paleo-ocean recorded by the EKOB underwent poly-cycle tectonic evolution (Yin and Zhang, 1997), among which the opening-closing cycle of the A'nyemaqen Ocean from the late Paleozoic to early Mesozoic was the latest tectonic event (Jiang et al., 1992; Mo et al., 2007). Along with the A'nyemaqen Ocean closing, active magmatism occurred and formed abundant granitoids constituting the main body of



the EKOB (Jiang et al., 1992; Li et al., 2013b; Mo et al., 2007). We consider the late Triassic mafic dikes from the EKOB were derived from the metasomatized subcontinental lithospheric mantle in response to post-collisional processes, whose nature remains unclear and requires further research, but we hypothesize the significance of asthenospheric upwelling, decompression melting, induced melting of metasomatized mantle lithosphere. Such mantle-derived alkaline basaltic melts are parental to the mafic dikes in the EKOB. Underplating and intrusion of such melts in the deep crust represent juvenile crustal material, whose melting produced the felsic volcanic rocks. We further hypothesize that much of the volumetrically significant contemporary granitoids, including the A-type granite, likely represent different products of the same thermal event (Hu et al., in preparation).

The timing of A'nyemaqen Ocean closing and continental collision is thought to be the early to middle Triassic (Pan et al., 2012; Xia et al., 2014; Yang et al., 2009) or late Triassic (Guo et al., 1998; Liu et al., 1984; Luo et al., 2002; Mo et al., 2007). Hence, the late Triassic volcanism in particular and the large scale granitoid magmatism in general in the EKOB are associated with post-collisional processes. Mantle plumes (Chung and Jahn, 1995; Hoek and Seitz, 1995; Lightfoot et al., 1993; Srivastava, 2011; Stepanova and Stepanov, 2010), slab break-off (Blanckenburg and Davies, 1995; Caprarelli and Leitch, 2001; Davies and von Blanckenburg, 1995; Maury et al., 2000; Xu et al., 2008) and convective lithosphere removal (Corrigan and Hanmer, 1997; Hoernle et al., 2006; Tatsumi and Kimura, 1991; Turner et al., 1996; Williams et al., 2001) are popular interpretations for asthenospheric upwelling and

related magmatism, but we consider that post-collisional lithosphere extension and orogenic collapse are most likely the major cause to consider, which is in nature a hypothesis to be tested.

## 6. Conclusion

1. The mafic dikes (diabase) and felsic volcanic rocks (rhyolitic tuff and rhyolite porphyry) from the EKOB synchronously emplaced in the late Triassic (from 228 to 218 Ma).
2. Geochemical data suggest that most of the mafic dikes in the EKOB are highly evolved alkaline basaltic rocks. Their parental melts were likely derived from subcontinental lithospheric mantle metasomatized in a mantle wedge environment (with terrestrial sediment input). Crustal contamination is also important and the overall contribution of mature crustal materials may be up to ~ 35%.
3. The felsic volcanic rocks were generated from mixing (melting and melt hybridization) of 45-50% crustal materials and 50-55% mantle-derived alkaline mafic melts represented by the mafic dikes. Such mantle-derived melts underplated and intruded the deep crust as juvenile crustal materials. Partial melting of such juvenile crustal materials produced felsic melts parental to the felsic volcanic rocks in the EKOB.
4. We consider that the late Triassic mafic dikes and felsic volcanic rocks are associated with post-collisional extension and related orogenic collapse. Such processes are most likely and significant to cause asthenospheric upwelling,

decompression melting and induced melting of prior metasomatized mantle lithosphere (e.g., during subduction episode) or even crustal melting. It is conceptually important for understanding the origin of the juvenile crust and continental crustal accretion through magmatism in the broad context of orogenesis from seafloor subduction to continental collision and to post-collisional processes.

## Acknowledgements

This work is supported by NSFC grants (41130314, 91014003), and grants by the Chinese Academy of Sciences, Shandong Province and the City of Qingdao to Yaoling Niu. We thank Zhenxing Hu, Yuxin Ma, Wenli Sun, Jinju Liu and Huixia Cui for help with sample preparation, and Lian Zhou, Jianxin Zhao, Yuexing Feng, Pengyuan Guo and Pu Sun for assistance with isotope analysis. We also thank Di-Cheng Zhu (guest editor) and the two anonymous reviewers for their detailed and constructive comments.

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## Captions

**Fig. 1** (a) Outline of the geological framework of the Greater Tibetan Plateau with several sutures: IYS, Indus-Yarlung Zangbo suture; BNS, Bangong-Nujiang suture; JS, Jinsha suture; AKMS, A'nyemaqen-Kunlun-Mutztagh suture; SQS, South Qilian suture; DHS, Danghe Nan Shan suture; NQS, North Qilian suture (after Niu et al., 2013; Yin and Harrison, 2000). (b) Schematic geological map of the East Kunlun Orogenic Belt (EKOB) showing two major faults (Central Kunlun Fault and South Kunlun Fault) and corresponding zones, i.e., northern, middle and southern zones (after Jiang et al., 1992). (c) Simplified distribution map of intrusive (granitoids) and volcanic rocks ( $T_{3e}$  &  $T_{3b}$ ) along the EKOB (modified from 1:1,000,000 geological map of northern Tibetan Plateau (Institute of Geology and Mineral Resources, Xi'an, China, 2006). The abbreviations beside the sample locations denote the Yeniugou area (YNG), Tufangzi area (QMX), Dulan area (DL) (Ding et al., 2011), Reshui area (RSX) and Yingde'er area (YDE), and the ages for sample locations are new data of this study except for the "DL" age from Ding et al. (2011).

**Fig. 2** (a) Outcrop of diabasic dikes intruding the A-type granite in the East Kunlun Orogenic Belt. (b) Field photos of chilled margins in the mafic dikes (left) and the schematic illustration of their emplacement (right). When the hot mafic magmas [I] intruded the cold A-type granite, they were quenched and developed chilled margins at the contact with the granite. These dikes may serve as conduit for subsequent mafic magma [II] transport with chilled margins developed at the contact with [I] if [I] were

sufficiently cold (e.g.,  $> 200^{\circ}\text{C}$  cooler). Photomicrographs of the diabase (c), rhyolitic tuff (d) and rhyolite porphyry (e).

**Fig. 3** Cathodoluminescence images of representative zircons from the diabase (a. YNG12-03), rhyolitic tuff (b. QMX12-01) and rhyolite porphyry (c. RSX12-48) of the late Triassic mafic dikes and felsic volcanic rocks from the East Kunlun Orogenic Belt. The circles with numbers are analysis spots of zircon U-Pb dating, indicating their ages (Ma) which are given in Table 2.

**Fig. 4** Concordia diagrams of dated zircons from sample (a) YNG13-03 (diabase), (b) QMX12-01 (rhyolitic tuff) and (c) RSX12-48 (rhyolite porphyry) of the late Triassic mafic dikes and felsic volcanic rocks from the East Kunlun Orogenic Belt.

**Fig. 5** Total alkalis vs.  $\text{SiO}_2$  (Le Bas et al., 1986) (a) and  $\text{K}_2\text{O}$  vs.  $\text{SiO}_2$  (b) diagrams of the late Triassic mafic dikes and felsic volcanic rocks from the East Kunlun Orogenic Belt. The dashed alkaline-subalkaline division line is from Irvine and Baragar (1971). The compositional fields of tholeiitic (TH), low-K calc-alkaline (CA), high-K calc-alkaline (K-CA) and shoshonite (SH) rock series are from Rickwood (1989).

**Fig. 6**  $\text{SiO}_2$  variation diagrams of the late Triassic mafic dikes and felsic volcanic rocks from the East Kunlun Orogenic Belt.

**Fig. 7** Normalized rare earth element (REE) and multi-element diagrams of the late Triassic mafic dikes and felsic volcanic rocks from the East Kunlun Orogenic Belt. Average ocean island basalts (OIB), bulk continental crust (BCC), upper continental crust (UCC) and lower continental crust (LCC) compositions are also plotted for comparison. Chondrite, primitive mantle and OIB data are from Sun and McDonough (1989). CC values are from Rudnick and Gao (2003).

**Fig. 8** Nb/Th (a), Ta/U (b),  $^{87}\text{Sr}/^{86}\text{Sr}$  (c) and  $\epsilon_{\text{Nd}(t)}$  (d) vs.  $\text{SiO}_2$  diagrams of the late Triassic mafic dikes and felsic volcanic rocks from the East Kunlun Orogenic Belt. Except for the high Nb-Ta rhyolite (Ding et al., 2011), the weak negative Nb/Th, Ta/U and  $\epsilon_{\text{Nd}(t)}$  correlations with  $\text{SiO}_2$  and the weak positive  $^{87}\text{Sr}/^{86}\text{Sr}$  correlation with  $\text{SiO}_2$  in mafic dikes (diabase) are consistent with crustal contamination during magma ascent. Average bulk continental crust (BCC) and upper continental crust (UCC) compositions are from Rudnick and Gao (2003).  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\epsilon_{\text{Nd}(t)}$  data of the UCC are from Goldstein and Jacobsen (1988).

**Fig. 9** (a) La/Nb vs. Th/Nb diagram, showing that the mafic dikes from the East Kunlun Orogenic Belt (EKOB) and OIB are similar with weak crustal assimilation, but differ from MORB and arc basalts (modified after Plank, 2005). (b)  $\epsilon_{\text{Nd}(0)}$  vs.  $\epsilon_{\text{Hf}(0)}$  diagram showing isotopically more enriched characteristics of the mafic dikes than MORB and even OIB (the latter data from Salters and White, 1998). (c) Zr vs. Zr/Y diagram, showing the mafic dikes plotting in the within-plate basalt field (after Pearce

and Norry, 1979; WPB, within plate basalts; MORB, mid-ocean ridge basalts; IAB, island arc basalts). Note that we plot the felsic volcanic rocks for comparison. (d)  $I_{Sr}$  vs.  $\epsilon_{Nd(t)}$  diagram of the late Triassic mafic dikes and felsic volcanic rocks from the EKOB. Isotopic fields compiled by Xiong et al. (2014b) are plotted for comparison (The high Nb-Ta rhyolites are not plotted due to their very low concentrations of Sr (Table 4), leading to extremely high and variable  $^{87}Rb/^{86}Sr$  ratios and thus unrealistic  $^{87}Sr/^{86}Sr$  ratios ( $I_{Sr}$ ) (Ding et al., 2011).

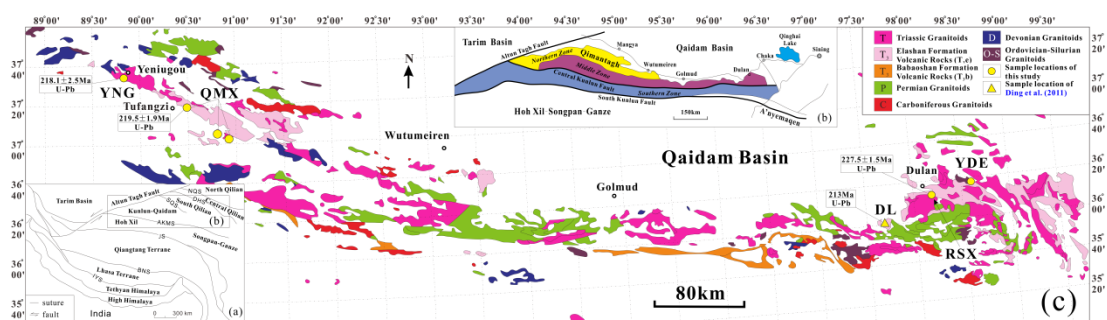
**Fig. 10** Diagram of  $Ta^*$  vs.  $Nb^*$  for the late Triassic mafic dikes and felsic volcanic rocks from the East Kunlun Orogenic Belt (after Niu and Batiza, 1997). Compared with common basalts, the diabasic dikes have Ta and Nb deficiencies, but significantly less so than continental crustal materials as well as the felsic volcanic rocks. These observations are consistent with the diabasic rocks gaining crustal contamination. Data of primitive mantle and average oceanic basalts (OIB, E-MORB, N-MORB) are from Sun and McDonough (1989). Crust composition (BCC, LCC, UCC) are from Rudnick and Gao (2003).

**Fig. 11** Co-variation diagrams of  $SiO_2$  and Rb with the abundances and ratios of other incompatible elements for the felsic volcanic rocks from the East Kunlun Orogenic Belt. (a), (b)  $Rb/Nb$  and  $Rb/Zr$  vs. Rb diagrams.  $Rb/Nb$  and  $Rb/Zr$  increase progressively with increasing Rb, implying an origin of crustal anatexis for the felsic volcanic rocks because magmas preserve or increase the LILE/HFSE ratios of  $Rb/Nb$

and Rb/Zr during crustal anatexis (Peccerillo et al., 2003). (c), (d)  $\text{Sr}/\text{Sr}^*$  and  $\text{Eu}/\text{Eu}^*$  vs.  $\text{SiO}_2$  diagrams showing the effect of plagioclase fractionation (see Table 3 for  $\text{Sr}/\text{Sr}^*$  and  $\text{Eu}/\text{Eu}^*$  calculation).

**Fig. 12** Showing  $I_{\text{Sr}}$  and  $\epsilon_{\text{Nd(t)}}$  compositions of the late Triassic mafic dikes and felsic volcanic rocks from the East Kunlun Orogenic Belt, which could be explained by mixing between a Paleo-Tethyan OIB and a Jinshuikou Granite. The Sr and Nd isotopes and elemental concentrations for the Paleo-Tethyan OIB are from the Permian OIB-type alkaline basalts in the Zhiduo and Zaduo areas of the Tethyan domain (Average composition:  $I_{\text{Sr}} = 0.703627$ ,  $\epsilon_{\text{Nd(t)}} = 4.5$ ,  $\text{Sr} = 658.3$  ppm,  $\text{Nd} = 39.6$  ppm) (Ma et al., 2007). The data of the Jinshuikou granite are from a cordierite granite pluton at the northeastern margin of the Greater Tibetan plateau which is derived from partial melting of metagreywacke in the upper continental crust (Average composition:  $I_{\text{Sr}} = 0.737417$ ,  $\epsilon_{\text{Nd(t)}} = -11.7$ ,  $\text{Sr} = 196.2$  ppm,  $\text{Nd} = 29.4$  ppm) (Ba et al., 2012). ( $K = (\text{Sr}/\text{Nd})_{\text{OIB}} / (\text{Sr}/\text{Nd})_{\text{Granite}}$ ,  $K_{\text{max}}$  and  $K_{\text{min}}$  represent the maximum and minimum values,  $K_{\text{average}}$  denotes the ratio from average Sr and Nd concentrations of OIB and granite respectively).

Fig. 1



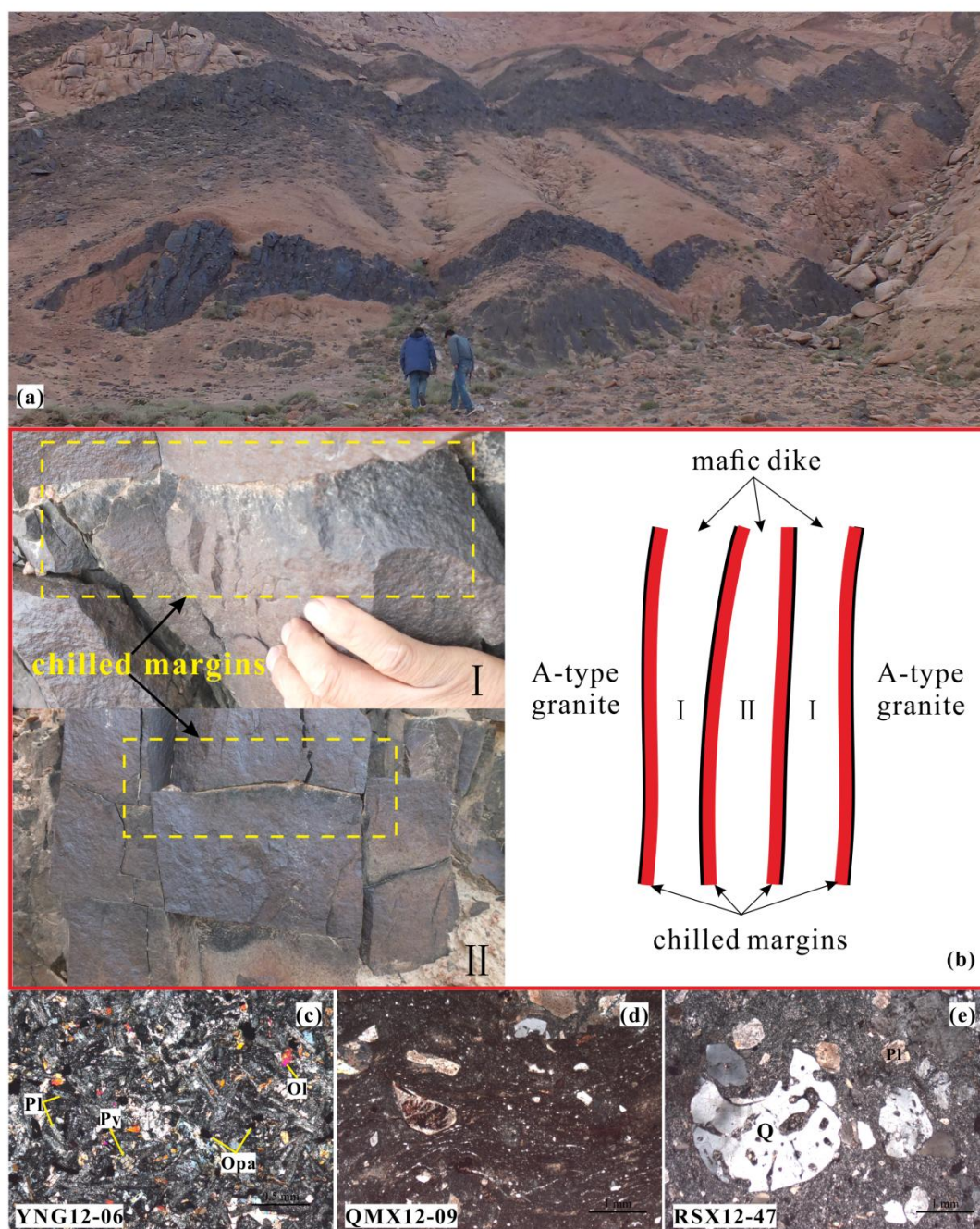
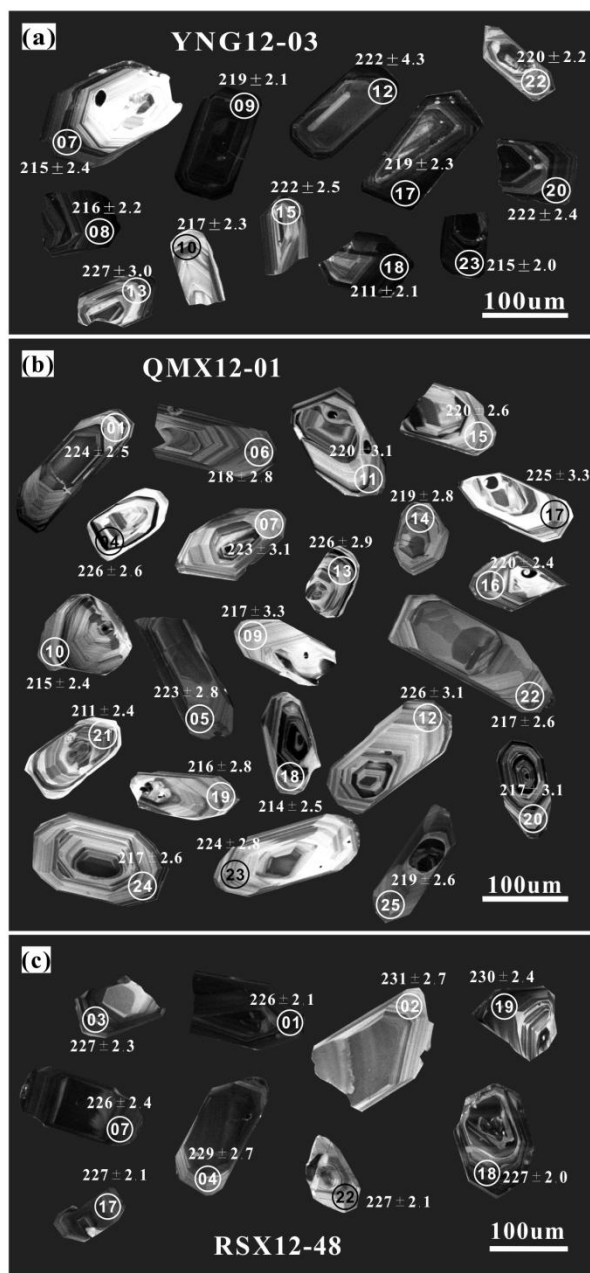
**Fig. 2**



Fig. 3



**Fig. 4**

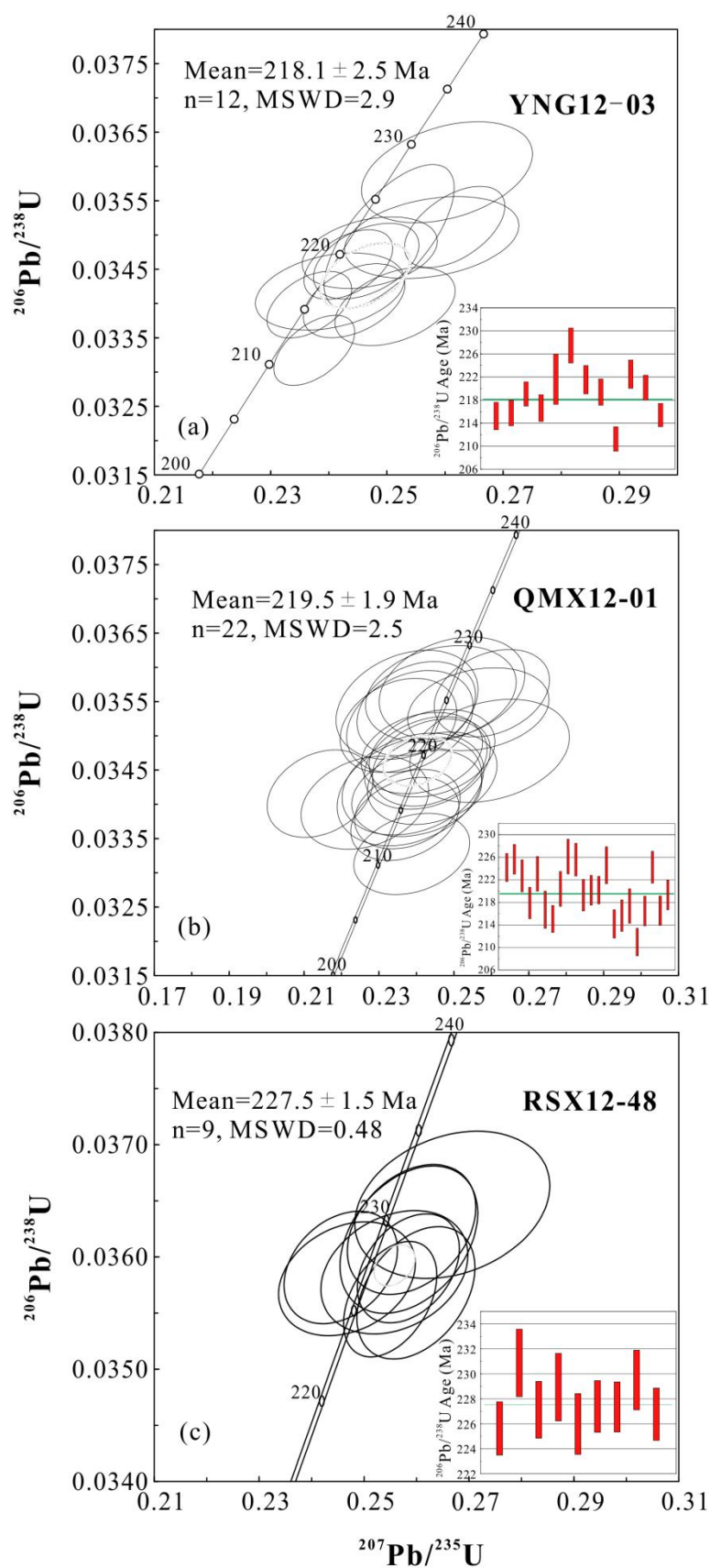
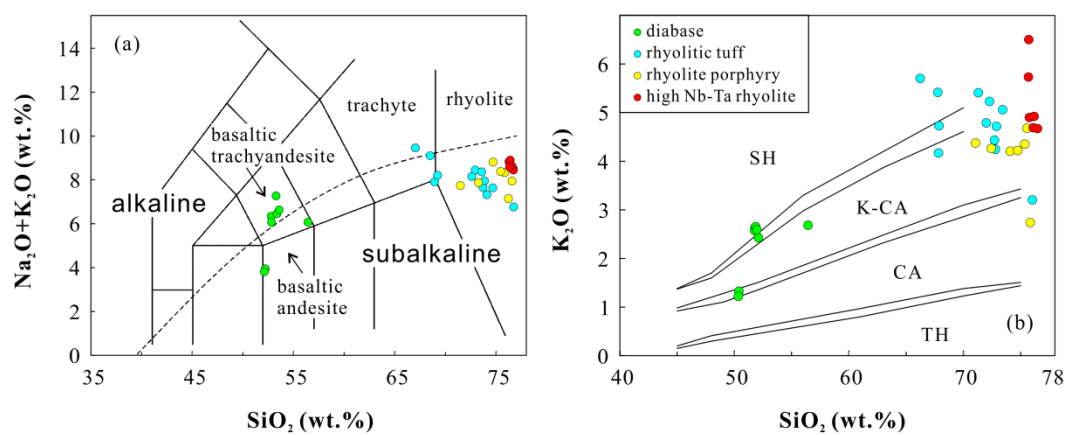
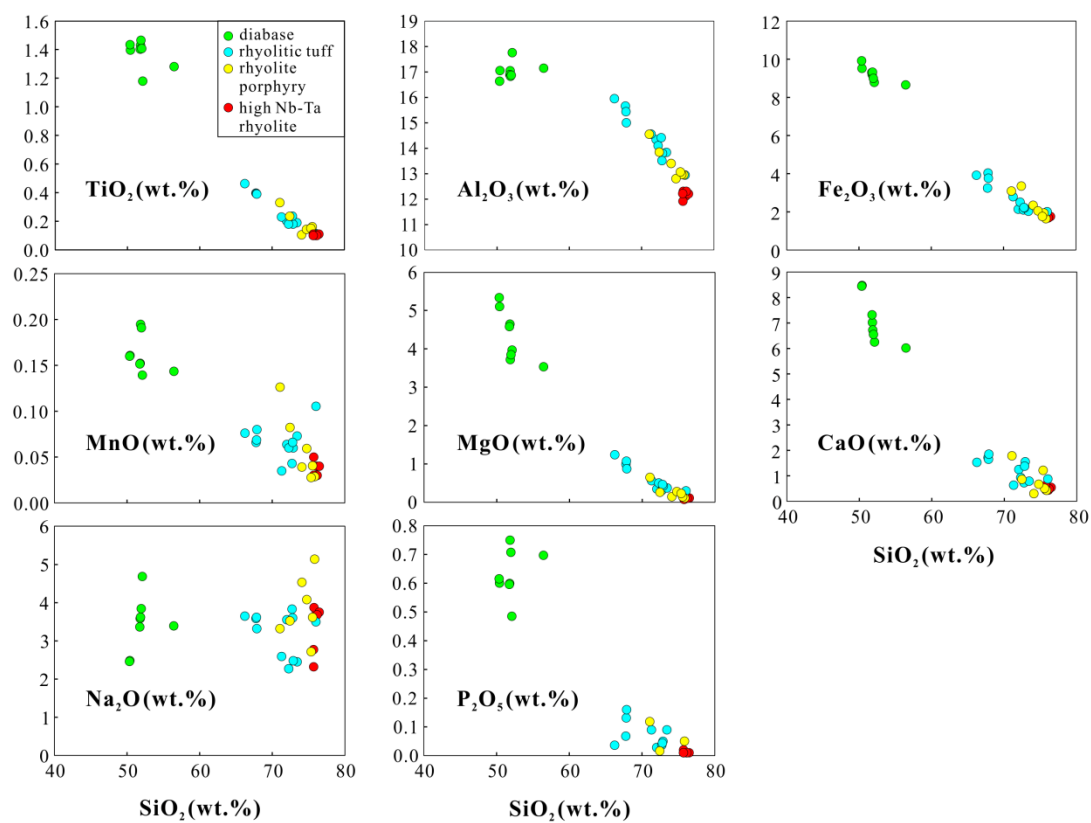


Fig. 5



**Fig. 6**

**Fig. 7**

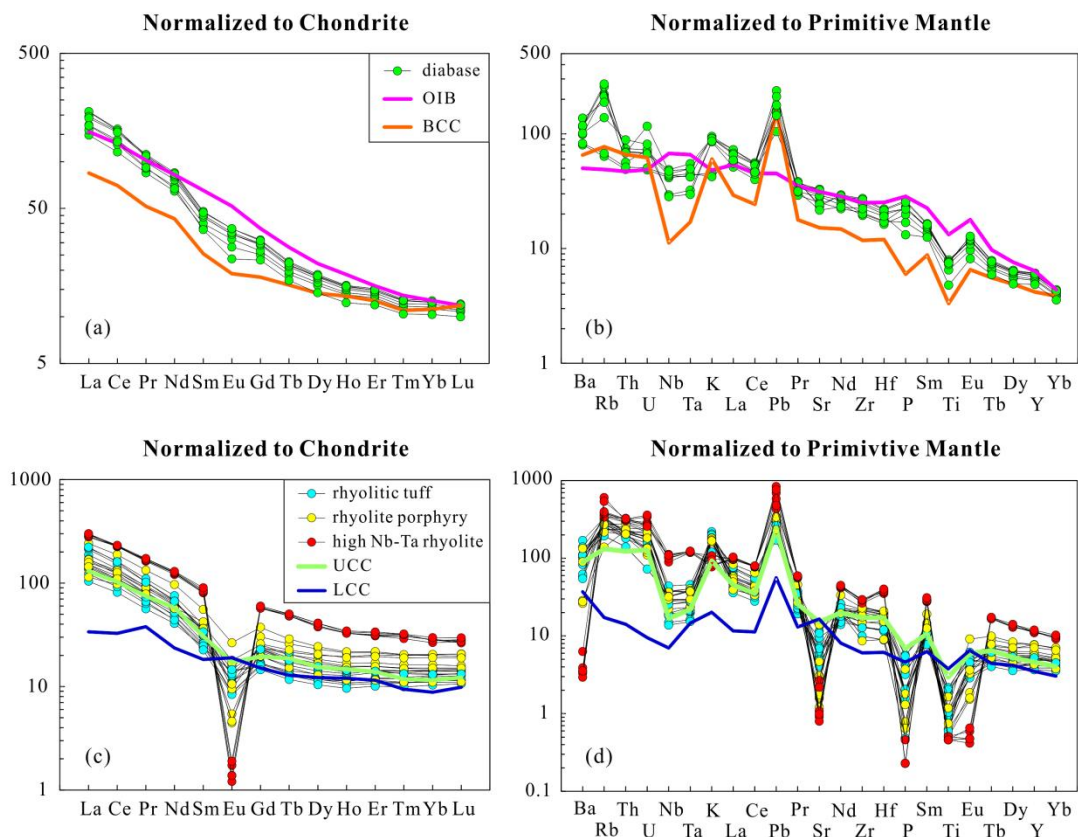
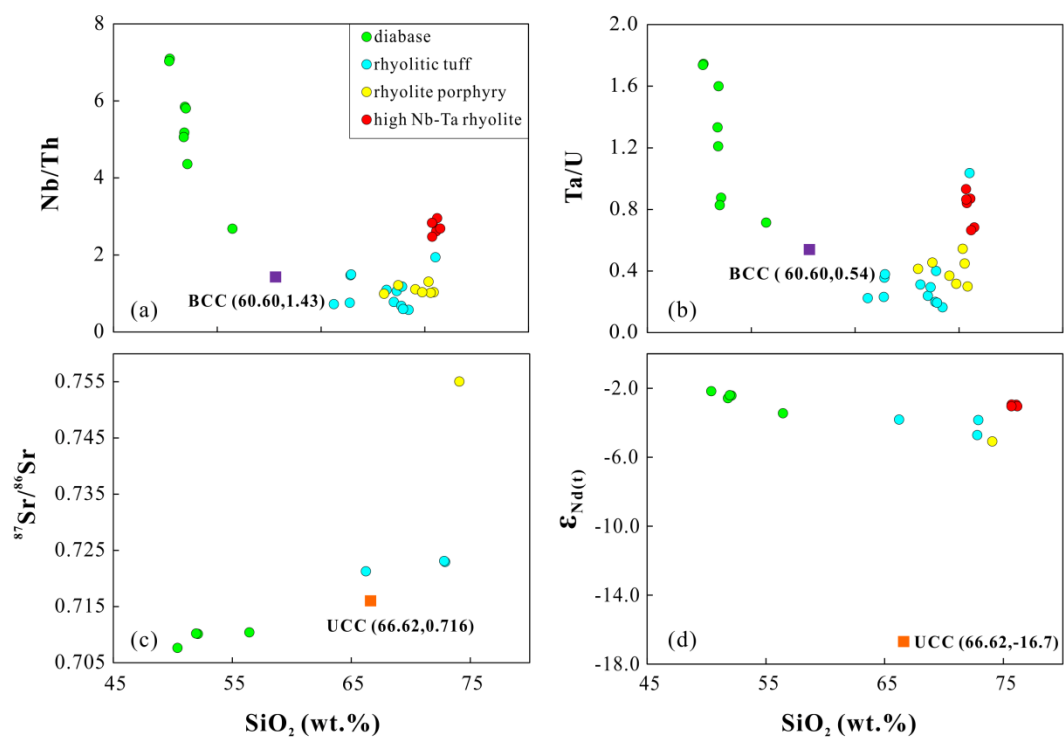
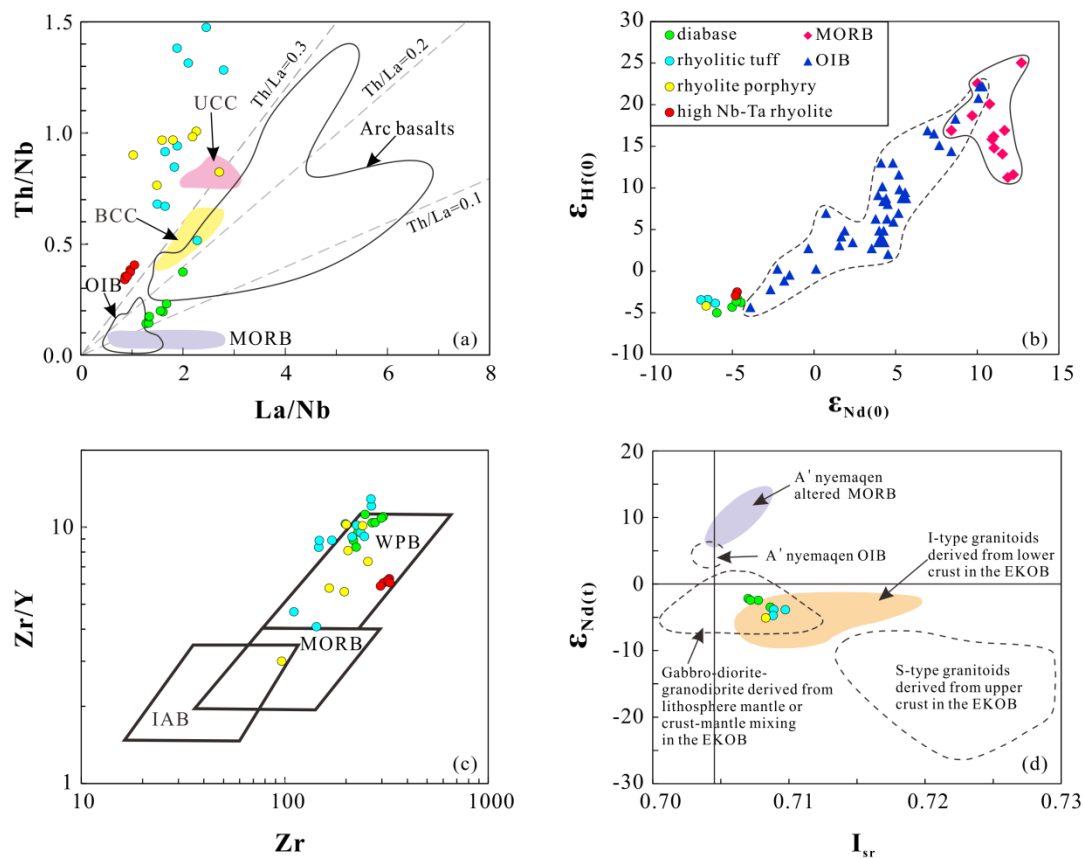


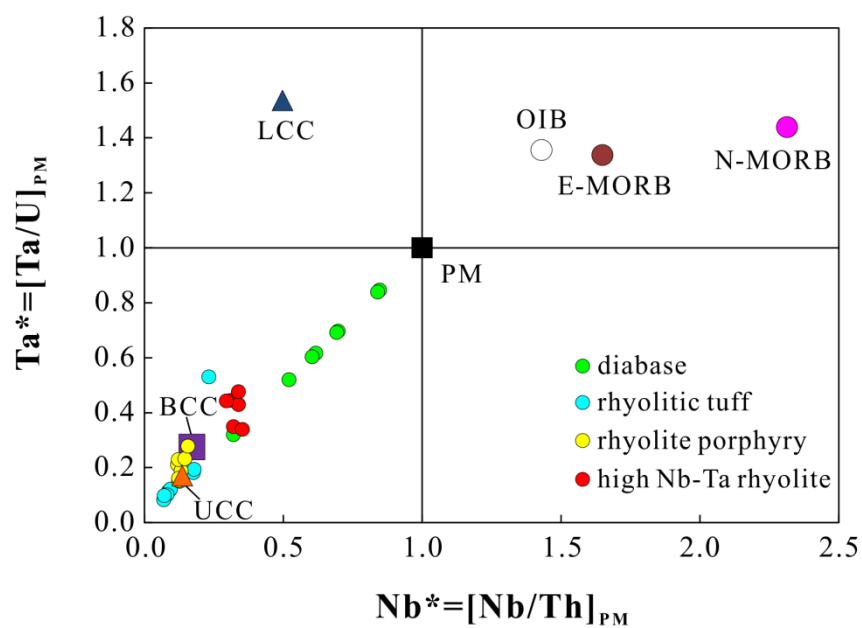
Fig. 8



**Fig. 9**

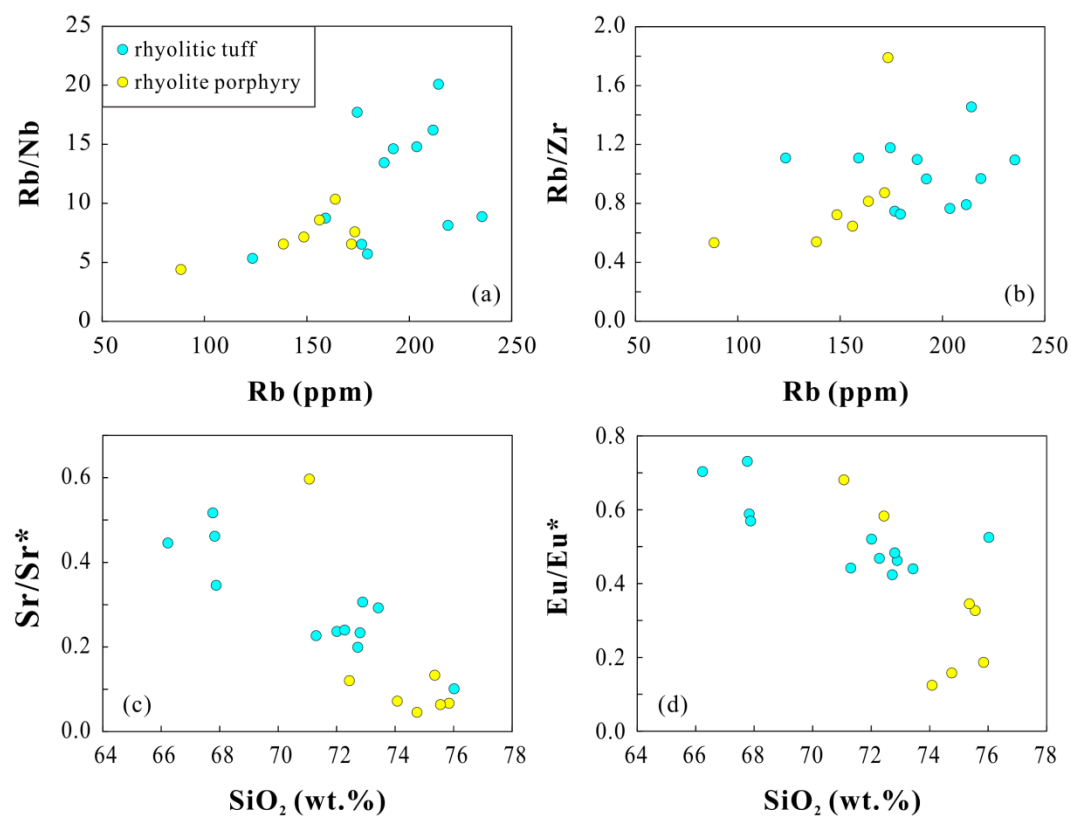


**Fig. 10**

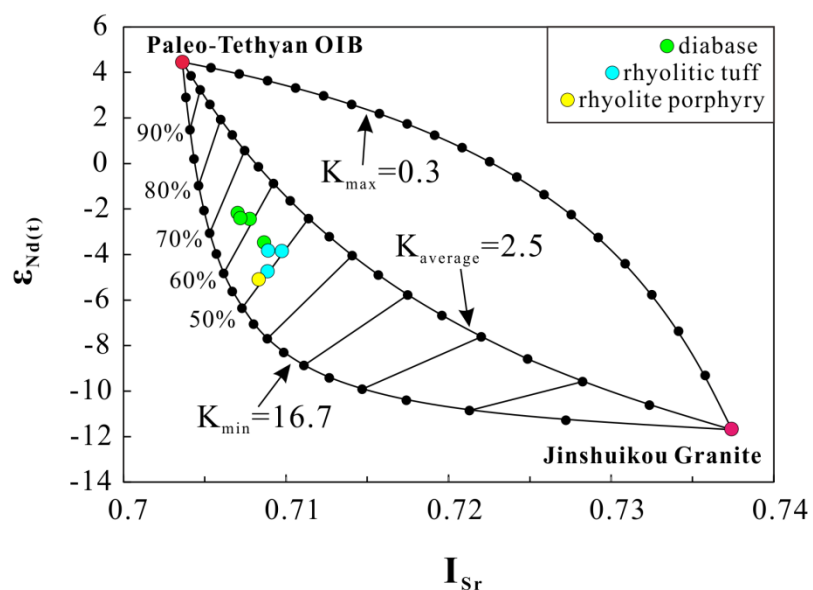




**Fig. 11**



**Fig. 12**



**Table 1**

Sample locations and zircon U-Pb ages of the late Triassic mafic dikes and felsic volcanic rocks in the East Kunlun Orogenic Belt.

Sample	GPS	Rock name	Age
YNG12-01	N37°34'30.3", E89°47'7.1"	diabase	218.1±2.5 Ma
YNG12-03	N37°34'30.3", E89°47'7.1"	diabase	
YNG12-04	N37°34'30.3", E89°47'7.1"	diabase	
YNG12-05	N37°34'30.3", E89°47'7.1"	diabase	
YNG12-06	N37°34'30.3", E89°47'7.1"	diabase	
YNG12-07	N37°34'30.3", E89°47'7.1"	diabase	
YNG12-08	N37°34'30.3", E89°47'7.1"	diabase	
QMX12-01	N37°18'34.8", E90°29'14.8"	rhyolitic tuff	219.5±1.9 Ma
QMX12-02	N37°18'34.9", E90°29'10.9"	rhyolitic tuff	
QMX12-03	N37°18'34.9", E90°29'9.0"	rhyolitic tuff	
QMX12-06	N37°18'42.1", E90°29'8.8"	rhyolitic tuff	
QMX12-07	N37°05'58.1", E90°47'58.3"	rhyolitic tuff	
QMX12-08	N37°05'58.1", E90°47'58.3"	rhyolitic tuff	
QMX12-09	N37°00'33.5", E90°56'23.8"	rhyolitic tuff	
QMX12-11	N37°00'33.5", E90°56'23.8"	diabase	
QMX12-10	N37°00'33.5", E90°56'23.8"	rhyolitic tuff	
QMX12-12	N37°00'33.5", E90°56'23.8"	rhyolitic tuff	
QMX12-13	N37°00'33.5", E90°56'23.8"	rhyolitic tuff	
RSX12-46	N36°10'55.9", E98°17'54.9"	rhyolite porphyry	
RSX12-47	N36°10'54.4", E98°17'53.4"	rhyolite porphyry	
RSX12-48	N36°10'46.7", E98°17'51.1"	rhyolite porphyry	227.5±1.5 Ma
RSX12-50	N36°10'46.7", E98°17'51.1"	rhyolite porphyry	
RSX12-51	N36°11'30.5", E98°13'58.9"	rhyolite porphyry	
YDE12-01	N36°18'45.4", E98°35'15.6"	rhyolitic tuff	
YDE12-02	N36°18'16.7", E98°36'40.5"	rhyolitic tuff	
YDE12-03	N36°17'13.2", E98°36'3.2"	rhyolite porphyry	
YDE12-16	N36°13'13.8", E98°42'21.92"	rhyolite porphyry	
DL09-01*	N36°00'38.64", E97°41'19.62"	high Nb-Ta rhyolite	
DL09-02*	N36°00'38.64", E97°41'19.62"	high Nb-Ta rhyolite	
DL09-03*	N36°00'38.64", E97°41'19.62"	high Nb-Ta rhyolite	212±2 Ma
DL09-04*	N36°00'38.64", E97°41'19.62"	high Nb-Ta rhyolite	
DL09-05*	N36°00'38.64", E97°41'19.62"	high Nb-Ta rhyolite	
DL09-06*	N36°00'38.64", E97°41'19.62"	high Nb-Ta rhyolite	

\* Data of high Nb-Ta rhyolite come from Ding et al. (2011).

**Table 2**

Zircon LA-ICP-MS U-Pb data of the late Triassic mafic dikes and felsic volcanic rocks from the East Kunlun Orogenic Belt.

Analysis spot	Pb (ppm)	Th (ppm)	U (ppm)	Th/ Isotopic ratios						Apparent age (Ma)							
				207Pb/206Pb		207Pb/235U		206Pb/238U		207Pb/206Pb		207Pb/235U		206Pb/238U			
				1σ	1σ	1σ	1σ	1σ	1σ	1σ	1σ	1σ	1σ	1σ	1σ		
YNG12-03 diabase, average age: 218.1±2.5 Ma, MSWD=2.9, n=12																	
01	92	331	101	0.3	0.0504	0.0017	0.2507	0.0082	0.0361	0.0004	213	78	227	7	229	3	
02	212	808	219	0.3	0.0509	0.0015	0.2742	0.0090	0.0390	0.0006	235	67	246	7	247	4	
03	92	242	865	0.2	0.0639	0.0024	0.3237	0.0126	0.0368	0.0004	739	81	285	10	233	3	
04	203	729	229	0.3	0.0507	0.0014	0.2636	0.0072	0.0377	0.0004	233	61	238	6	239	3	
05	199	795	210	0.3	0.0512	0.0013	0.2539	0.0065	0.0360	0.0004	250	59	230	5	228	2	
06	239	910	253	0.3	0.0513	0.0015	0.2628	0.0077	0.0370	0.0004	254	65	237	6	234	2	
07	335	137	376	0.3	0.0534	0.0013	0.2514	0.0068	0.0340	0.0004	346	56	228	6	215	2	
08	350	125	497	0.2	0.0518	0.0011	0.2444	0.0058	0.0340	0.0004	276	45	222	5	216	2	
09	490	188	589	0.3	0.0509	0.0010	0.2434	0.0050	0.0346	0.0003	235	44	221	4	219	2	
10	123	555	994	0.5	0.0512	0.0019	0.2402	0.0085	0.0342	0.0004	256	85	219	7	217	2	
11	312	700	254	0.2	0.0572	0.0013	0.5127	0.0126	0.0648	0.0007	498	45	420	8	405	4	
12	334	135	340	0.4	0.0523	0.0017	0.2504	0.0074	0.0350	0.0007	298	76	227	6	222	4	
13	146	551	139	0.4	0.0528	0.00	0.2603	0.00	0.0359	0.00	320	11	235	8	227	3	

		3	0		20	97	05	8				
14	346	118	411	0.2	0.00	0.00	0.00	0.00	306	56	267	6 261 3
	2	7	9	0.0525	13	0.3008	76	0.0414	05			
15	123	503	100	0.5	0.00	0.00	0.00	0.00	350	87	233	8 222 2
	8		0	0.0535	20	0.2577	99	0.0350	04			
16	362	121	368	0.3	0.00	0.00	0.00	0.00	287	55	254	5 249 2
	4	1	3	0.0520	11	0.2843	68	0.0394	04			
17	325	133	348	0.3	0.00	0.00	0.00	0.00	261	58	224	5 219 2
	3	6	8	0.0514	12	0.2464	60	0.0346	04			
18	636	250	756	0.3	0.00	0.00	0.00	0.00	261	41	216	4 211 2
	8	5	3	0.0515	09	0.2375	46	0.0333	03			
19	291	108	352	0.3	0.00	0.00	0.00	0.00	287	52	237	5 231 3
	2	5	1	0.0521	12	0.2633	62	0.0365	04			
20	611	218	688	0.3	0.00	0.00	0.00	0.00	367	72	236	5 222 2
	8	2	2	0.0537	10	0.2617	57	0.0351	04			
21	110	394	924	0.4	0.00	0.01	0.00	0.00	339	80	258	8 250 3
			3	0.0532	19	0.2898	03	0.0395	04			
22	157	644	154	0.4	0.00	0.00	0.00	0.00	254	70	224	6 220 2
		9	2	0.0513	16	0.2470	77	0.0347	03			
23	425	167	512	0.3	0.00	0.00	0.00	0.00	209	46	216	4 215 2
	6	1	3	0.0503	10	0.2367	48	0.0340	03			
24	167	438	658	0.6	0.00	0.01	0.00	0.00	322	78	366	1 373 4
		7		0.0527	18	0.4338	54	0.0596	07		1	

QMX12-

01

rhyolitic

tuff,

average

age:

219.5±1.

9 Ma,

MSWD=

2.5,

n=22

01	86	352	632	0.5	0.00	0.01	0.00	0.00	332	11	232	1 224 2
			6	0.0530	27	0.2565	25	0.0354	04	3		0
02	70	293	600	0.4	0.00	0.01	0.00	0.00	656	10	246	1 210 3
			9	0.0612	30	0.2744	26	0.0331	05	4		0
03	76	304	595	0.5	0.00	0.01	0.00	0.00	554	89	249	9 219 3
			1	0.0586	24	0.2783	13	0.0346	04			
04	93	378	759	0.5	0.00	0.01	0.00	0.00	345	95	235	8 226 3
			0	0.0531	21	0.2601	02	0.0356	04			
05	58	244	518	0.4	0.00	0.01	0.00	0.00	143	10	214	8 223 3
				0.0489		0.2352		0.0352				

			7		21		03		05		0					
06	65	285	595	0.4 8	0.0522	0.00 26	0.2442	0.01 14	0.0344	0.00 04	295	13 9	222	9	218	3
07	63	275	516	0.5 3	0.0493	0.00 24	0.2382	0.01 11	0.0352	0.00 05	165	11 7	217	9	223	3
08	66	232	472	0.4 9	0.0722	0.00 37	0.3477	0.01 79	0.0349	0.00 05	991	10 4	303	1 3	221	3
09	42	185	406	0.4 5	0.0515	0.00 29	0.2382	0.01 28	0.0342	0.00 05	261	13 1	217	1 0	217	3
10	89	414	749	0.5 5	0.0511	0.00 20	0.2376	0.00 93	0.0339	0.00 04	256	97	216	8	215	2
11	53	218	448	0.4 9	0.0546	0.00 30	0.2596	0.01 41	0.0348	0.00 05	398	92	234	1 1	220	3
12	46	186	410	0.4 5	0.0511	0.00 28	0.2495	0.01 28	0.0357	0.00 05	243	13 0	226	1 0	226	3
13	100	448	679	0.6 6	0.0501	0.00 26	0.2465	0.01 33	0.0356	0.00 05	211	12 2	224	1 1	226	3
14	57	252	508	0.5 0	0.0515	0.00 24	0.2429	0.01 11	0.0346	0.00 04	265	10 7	221	9	219	3
15	65	285	494	0.5 8	0.0517	0.00 25	0.2442	0.01 11	0.0347	0.00 04	333	11 8	222	9	220	3
16	103	453	787	0.5 7	0.0504	0.00 22	0.2415	0.01 07	0.0347	0.00 04	213	10 6	220	9	220	2
17	64	259	497	0.5 2	0.0487	0.00 26	0.2375	0.01 25	0.0355	0.00 05	200	12 4	216	1 0	225	3
18	131	580	104	0.5 6	0.0511	0.00 21	0.2369	0.00 95	0.0338	0.00 04	256	96	216	8	214	3
19	50	223	495	0.4 5	0.0486	0.00 24	0.2262	0.01 13	0.0340	0.00 04	128	-8 1	207	9	216	3
20	62	286	548	0.5 2	0.0508	0.00 27	0.2391	0.01 25	0.0343	0.00 05	232	12 4	218	1 0	217	3
21	80	342	777	0.4 4	0.0524	0.00 22	0.2388	0.01 02	0.0333	0.00 04	302	92	217	8	211	2
22	53	236	513	0.4 6	0.0462	0.00 21	0.2142	0.00 93	0.0342	0.00 04	9	11 3	197	8	217	3
23	57	245	514	0.4 8	0.0493	0.00 22	0.2399	0.01 05	0.0354	0.00 05	167	10 6	218	9	224	3
24	59	260	510	0.5 1	0.0512	0.00 25	0.2401	0.01 15	0.0342	0.00 04	250	83	218	9	217	3
25	67	290	628	0.4 6	0.0508	0.00 21	0.2436	0.01 01	0.0346	0.00 04	232	96	221	8	219	3

RSX12-4

8,  
rhyolite  
porphyry  
, average  
age:  
227.5±1.  
5 Ma,  
MSWD=  
0.48,  
n=9

01	293	122	273	0.4	0.0518	0.00	0.2550	0.00	0.0356	0.00	276	47	231	5	226	2
	0	5	5			12		59	03							
02	59	241	448	0.5	0.0531	0.00	0.2668	0.01	0.0365	0.00	332	10	240	1	231	3
			4			25		23	04			7		0		
03	127	555	828	0.6	0.0521	0.00	0.2558	0.00	0.0359	0.00	300	89	231	7	227	2
			7			20		92		04						
04	147	688	864	0.8	0.0523	0.00	0.2585	0.00	0.0362	0.00	298	80	233	7	229	3
			0			18		87		04						
05	196	727	211	0.3	0.0539	0.00	0.2766	0.00	0.0370	0.00	369	63	248	7	234	3
			6	4		15		86		05						
06	143	627	900	0.7	0.0551	0.00	0.2792	0.01	0.0368	0.00	413	83	250	8	233	3
			0			20		01		04						
07	181	742	165	0.4	0.0526	0.00	0.2599	0.00	0.0357	0.00	309	65	235	6	226	2
			0	5		15		74		04						
08	204	862	133	0.6	0.0684	0.00	0.3347	0.01	0.0353	0.00	880	-1	293	9	224	2
			1	5		25		21		04		23				
09	193	771	165	0.4	0.0525	0.00	0.2722	0.00	0.0376	0.00	306	55	244	5	238	2
			1	7		13		67		04						
10	62	214	275	0.7	0.0533	0.00	0.3141	0.01	0.0429	0.00	343	13	277	1	271	4
			8			31		72		06		3		3		
11	118	430	647	0.6	0.0796	0.00	0.4402	0.03	0.0378	0.00	1187	13	370	2	239	3
			6			55		64		05		7		6		
12	113	425	725	0.5	0.0663	0.00	0.3582	0.01	0.0389	0.00	817	89	311	1	246	4
			9			28		61		06				2		
13	531	762	183	0.4	0.1502	0.00	0.8778	0.01	0.0424	0.00	2350	42	640	1	268	3
			8	1		37		99		04				1		
14	282	119	216	0.5	0.0542	0.00	0.2771	0.00	0.0369	0.00	376	59	248	6	234	2
			4	1		14		72		04						
15	986	361	746	0.4	0.0670	0.00	0.3344	0.01	0.0353	0.00	839	60	293	9	223	3
			5	3		19		21		04						
16	165	677	123	0.5	0.0548	0.00	0.2813	0.00	0.0371	0.00	467	73	252	7	235	2
			7	5		17		88		03						
17	229	107	155	0.6	0.0498	0.00	0.2456	0.00	0.0359	0.00	183	66	223	6	227	2

	1	3	9		15	71	03							
	109	268	0.4		0.00	0.00	0.00							
18	267	3	8	1	0.0522	0.2584	0.0359	0.00	295	57	233	5	227	2
								03						
	192	860	135	0.6		0.00	0.00	0.00						
19		2	4		0.0521	0.2591	0.0362	0.00	287	77	234	7	230	2
								04						
	171	684	125	0.5		0.00	0.01	0.00						
20		1	5		0.0597	0.2996	0.0362	0.00	591	81	266	9	229	2
								03						
	142	617	768	0.8		0.00	0.01	0.00						
21			0		0.0583	0.2996	0.0372	0.00	539	83	266	9	235	3
								04						
	197	927	113	0.8		0.00	0.00	0.00						
22		9	1		0.0501	0.2467	0.0358	0.00	198	77	224	7	227	2
								03						



**Table 3**

Whole-rock major and trace element data of the late Triassic mafic dikes and felsic volcanic rocks in the East Kunlun Orogenic Belt.

	YNG12	YNG12	YNG12	YNG12	YNG12	YNG12	YNG12	QMX1	QMX1	QMX1	QMX1
Sample	-01	-03	-04	-05	-06	-07	-08	2-11	2-01	2-02	2-03
	<i>mafic</i> <i>(diabas</i> <i>e)</i>							<i>felsic</i> <i>(rhyoliti</i> <i>c tuff)</i>			
<i>Major</i> <i>element</i> <i>(wt.%)</i>											
SiO2	52.11	50.40	50.35	51.82	51.76	51.86	51.97	56.44	66.23	67.76	72.01
TiO2	1.18	1.40	1.44	1.43	1.40	1.47	1.41	1.28	0.46	0.40	0.20
Al2O3	17.76	17.06	16.64	17.05	16.90	16.83	16.87	17.15	15.95	15.66	14.34
Fe2O3 a	8.78	9.52	9.91	9.20	9.30	9.32	9.00	8.65	3.91	3.24	2.14
MnO	0.14	0.16	0.16	0.15	0.15	0.19	0.19	0.14	0.08	0.07	0.06
MgO	3.97	5.11	5.34	4.65	4.59	3.72	3.85	3.54	1.24	0.99	0.35
CaO	6.25	8.47	8.45	7.02	7.32	6.72	6.55	6.02	1.53	1.71	1.25
Na2O	4.68	2.48	2.46	3.58	3.36	3.62	3.84	3.39	3.65	3.58	3.55
K2O	2.43	1.33	1.22	2.64	2.58	2.66	2.59	2.69	5.70	5.42	4.79
P2O5	0.48	0.60	0.62	0.60	0.60	0.75	0.71	0.70	0.04	0.07	0.03
LOI b	1.49	3.13	2.96	1.64	1.53	2.72	2.74	2.13	0.63	0.79	0.64
Total	99.27	99.65	99.54	99.78	99.49	99.86	99.72	102.13	99.42	99.70	99.36
Mg# c	0.50	0.54	0.54	0.53	0.52	0.47	0.49	0.47	0.41	0.40	0.26
<i>Trace</i> <i>element</i> <i>(ppm)</i>											
Sc	21.6	21.3	22.5	22.3	21.9	20.0	19.6	13.0	6.07	5.33	3.23
V	178	169	186	168	168	155	147	96.7	29.2	32.3	8.55
Cr	51.0	95.0	94.1	84.5	80.7	68.2	65.1	30.2	4.85	5.94	3.06
Co	21.7	26.2	26.3	22.6	23.3	21.2	21.0	14.9	5.46	5.09	1.25
Ni	14.5	42.8	42.5	29.3	33.6	28.3	26.5	14.0	2.01	2.81	0.73
Ga	19.1	17.5	18.1	18.4	18.6	18.5	18.0	17.6	17.2	18.3	15.4
Rb	140	40.4	42.7	135	119	163	172	88.0	212	204	188
Sr	531	599	611	695	681	492	513	456	155	199	112
Y	24.0	24.5	26.9	25.9	26.7	27.7	27.5	22.2	22.1	20.6	19.2
Zr	230	218	225	269	279	305	299	249	267	266	171

Nb	20.922	29.565	30.631	30.821	31.930	34.631	33.755	20.206	13.060	13.768	13.966
Cs	4.448	3.744	4.206	10.110	11.766	8.762	5.240	8.152	4.852	4.856	6.572
Ba	691.00	559.20	574.40	818.60	958.20	806.60	822.20	705.80	1184.40	977.40	580.80
Hf	5.345	5.040	5.270	6.138	6.398	6.826	6.661	5.900	6.252	6.149	4.407
Ta	1.322	1.774	1.840	1.728	2.026	2.250	2.026	1.216	0.806	0.849	0.966
Pb	10.766	11.254	7.424	16.858	11.014	14.966	12.620	10.262	21.480	20.380	21.560
Th	4.796	4.164	4.352	5.952	6.308	5.922	5.810	7.528	18.034	18.088	17.910
U	1.510	1.017	1.059	1.428	1.520	1.407	2.448	1.704	3.612	3.676	4.050
La	35.16	37.96	40.86	49.66	49.92	46.46	45.30	40.44	24.66	29.04	39.06
Ce	70.80	79.12	84.64	97.60	99.34	96.80	94.88	82.14	49.66	56.42	74.82
Pr	8.04	8.60	9.40	10.20	10.38	10.57	10.34	8.71	5.34	6.02	7.62
Nd	30.14	32.44	35.68	37.32	38.18	39.68	38.94	31.30	18.96	20.74	24.88
Sm	5.71	6.11	6.72	6.73	6.94	7.31	7.20	5.58	3.68	3.65	4.12
Eu	1.63	1.84	1.97	1.97	2.03	2.14	2.15	1.37	0.81	0.82	0.64
Gd	5.17	5.47	6.06	5.96	6.10	6.44	6.35	4.77	3.42	3.22	3.48
Tb	0.70	0.73	0.81	0.78	0.80	0.85	0.83	0.64	0.53	0.48	0.51
Dy	4.05	4.22	4.62	4.45	4.58	4.76	4.67	3.62	3.35	2.95	2.98
Ho	0.79	0.81	0.88	0.85	0.87	0.90	0.89	0.70	0.72	0.64	0.61
Er	2.19	2.27	2.47	2.36	2.41	2.51	2.46	1.97	2.25	2.01	1.85
Tm	0.29	0.30	0.32	0.31	0.32	0.33	0.33	0.27	0.35	0.31	0.28
Yb	1.91	1.96	2.11	2.05	2.11	2.16	2.11	1.76	2.39	2.18	1.93
Lu	0.27	0.28	0.30	0.29	0.30	0.31	0.30	0.25	0.36	0.34	0.29
(La/Yb)											
Nd	13.22	13.90	13.89	17.41	16.99	15.44	15.40	16.50	7.41	9.56	14.53
Eu/Eu*	0.92	0.97	0.95	0.95	0.95	0.96	0.97	0.81	0.70	0.73	0.52
e											
Sr/Sr* e	0.99	1.04	0.97	1.03	0.99	0.70	0.74	0.80	0.45	0.52	0.24

Table 3  
(continued)

Sample	QMX1 2-06	QMX1 2-07	QMX1 2-08	QMX1 2-09	QMX1 2-10	QMX1 2-12	QMX1 2-13	YDE12 -01	YDE12 -02	RSX12- 46	RSX12- 47
										<i>felsic</i> ( <i>rhyolite</i> <i>porphyry</i> )	

*Major  
element  
(wt.%)*

SiO <sub>2</sub>	72.72	73.43	72.89	71.30	67.83	72.28	67.88	76.02	72.80	71.07	75.84
TiO <sub>2</sub>	0.21	0.19	0.18	0.23	0.39	0.18	0.39	0.11	0.24	0.33	0.11
Al <sub>2</sub> O <sub>3</sub>	14.42	13.84	13.80	14.56	15.44	14.10	15.01	12.94	13.51	14.56	12.95
Fe <sub>2</sub> O <sub>3</sub> a	2.09	2.03	2.20	2.79	4.03	2.50	3.76	2.0	2.22	3.09	1.64
MnO	0.04	0.07	0.06	0.04	0.07	0.06	0.08	0.11	0.07	0.13	0.03
MgO	0.31	0.37	0.42	0.56	1.07	0.50	0.87	0.30	0.46	0.65	0.11
CaO	0.72	0.79	1.55	0.63	1.65	0.93	1.85	0.87	1.38	1.78	0.43
Na <sub>2</sub> O	3.83	2.45	2.48	2.59	3.62	2.27	3.32	3.50	3.60	3.32	5.14
K <sub>2</sub> O	4.44	5.06	4.72	5.41	4.17	5.23	4.73	3.21	4.25	4.37	2.74
P <sub>2</sub> O <sub>5</sub>	0.04	0.09	0.05	0.09	0.13	<0.03	0.16	<0.03	0.04	0.12	0.05
LOI b	0.57	0.77	0.71	0.87	1.22	0.87	1.11	0.62	0.67	0.40	0.19
Total	99.40	99.09	99.06	99.06	99.62	98.92	99.16	99.68	99.24	99.81	99.23

Mg# c	0.25	0.29	0.30	0.31	0.37	0.31	0.34	0.25	0.31	0.32	0.13
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*Trace  
element  
(ppm)*

Sc	2.95	3.13	3.03	3.61	6.66	3.63	6.84	4.44	5.07	5.52	4.67
V	6.75	12.1	11.6	10.2	37.8	9.99	30.8	4.02	9.08	26.5	3.40
Cr	4.93	3.82	7.37	7.68	14.3	5.67	14.1	2.67	3.82	6.31	3.55
Co	1.04	1.62	1.74	1.89	5.06	1.60	4.66	0.69	1.32	2.90	0.17
Ni	1.76	1.86	3.57	3.47	6.42	2.36	5.83	1.94	1.25	3.11	0.71
Ga	15.7	15.7	14.6	17.4	17.3	17.1	18.9	15.8	16.0	18.1	16.9
Rb	192	214	175	219	177	235	179	123	159	164	88.5
Sr	85.5	126	120	124	244	146	229	60.9	105	295	33.3
Y	19.3	17.6	16.7	22.2	24.8	23.4	26.8	23.8	35.1	19.6	28.7
Zr	199	147	148	226	236	215	247	111	144	201	166
Nb	13.140	10.667	9.851	26.910	27.018	26.514	31.392	23.100	18.180	15.824	20.106
Cs	4.984	3.988	3.644	5.188	5.468	5.674	4.224	3.830	6.830	4.568	1.851
Ba	406.80	436.80	383.00	778.80	758.60	699.80	765.60	761.20	766.20	775.40	200.00
Hf	4.794	3.708	3.552	5.480	5.819	5.334	6.191	2.738	3.702	5.080	4.740
Ta	0.868	0.664	0.628	1.491	1.652	1.545	1.878	1.582	1.146	0.960	1.178
Pb	21.620	19.482	15.924	16.254	23.660	15.846	21.060	12.220	18.922	32.320	13.876
Th	19.374	18.540	16.540	24.600	18.338	24.940	20.980	11.886	15.366	15.928	19.442

U	4.358	4.048	3.238	4.786	4.642	5.248	4.954	1.528	2.862	2.318	3.928
La	32.34	35.80	32.46	44.50	40.50	50.18	51.92	52.70	33.36	35.82	32.08
Ce	63.90	66.86	61.70	83.82	77.70	93.92	99.58	98.44	65.28	71.38	66.78
Pr	6.78	6.90	6.28	8.77	8.28	9.72	10.45	9.68	6.95	7.67	7.59
Nd	22.74	22.38	20.50	28.78	28.40	31.78	35.22	31.22	24.24	26.74	27.26
Sm	3.97	3.78	3.45	4.81	5.05	5.25	6.02	5.17	4.85	4.74	5.41
Eu	0.51	0.50	0.48	0.63	0.92	0.73	1.04	0.85	0.77	0.97	0.31
Gd	3.38	3.26	2.99	3.99	4.52	4.38	5.19	4.70	4.87	4.03	4.89
Tb	0.50	0.48	0.44	0.60	0.68	0.64	0.77	0.67	0.80	0.57	0.76
Dy	3.07	2.86	2.64	3.58	4.02	3.79	4.42	3.97	5.10	3.28	4.67
Ho	0.64	0.59	0.54	0.75	0.82	0.78	0.89	0.81	1.10	0.65	0.95
Er	1.95	1.76	1.67	2.34	2.40	2.35	2.59	2.33	3.34	1.91	2.80
Tm	0.30	0.28	0.25	0.36	0.36	0.36	0.38	0.34	0.51	0.28	0.41
Yb	2.11	1.91	1.75	2.47	2.39	2.46	2.56	2.22	3.44	1.87	2.75
Lu	0.32	0.29	0.27	0.37	0.36	0.37	0.38	0.34	0.52	0.28	0.40

(La/Yb)

N d	10.99	13.48	13.28	12.90	12.17	14.63	14.56	17.0	6.95	13.74	8.36
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Eu/Eu*	0.42	0.44	0.46	0.44	0.59	0.47	0.57	0.52	0.48	0.68	0.19
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Sr/Sr* e	0.20	0.29	0.31	0.23	0.46	0.24	0.35	0.10	0.23	0.60	0.07
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Table 3  
(continued)

	RSX12-48	RSX12-50	RSX12-51	YDE12-03	YDE12-16	DL09-01	DL09-02	DL09-03	DL09-04	DL09-05	DL09-06
Sample	48	50	51	-03	-16	1	2	3	4	5	6
<i>felsic</i>						<i>felsic</i>					
<i>(rhyolite</i>						<i>(high</i>					
<i>e</i>						<i>Nb-Ta</i>					
<i>porphyry)</i>						<i>rhyolite)</i>					
Major element (wt.%)											
SiO <sub>2</sub>	74.08	75.56	74.75	72.44	75.36	76.10	75.76	75.71	76.48	76.18	75.69
TiO <sub>2</sub>	0.11	0.16	0.14	0.24	0.15	0.10	0.10	0.11	0.11	0.10	0.10
Al <sub>2</sub> O <sub>3</sub>	13.40	12.97	12.81	13.85	13.07	12.12	12.31	11.92	12.21	12.31	12.22
Fe <sub>2</sub> O <sub>3</sub>	2.34	1.93	2.05	3.35	1.75	1.81	1.82	1.83	1.76	1.68	1.82

a

MnO	0.04	0.04	0.06	0.08	0.03	0.04	0.03	0.05	0.04	0.03	0.03
MgO	0.14	0.14	0.28	0.26	0.23	0.14	0.07	0.12	0.11	0.10	0.16
CaO	0.30	0.50	0.67	0.86	1.21	0.44	0.44	0.51	0.54	0.49	0.61
Na <sub>2</sub> O	4.53	3.62	4.08	3.52	2.72	3.75	3.87	2.32	3.75	3.68	2.77
K <sub>2</sub> O	4.21	4.68	4.22	4.26	4.35	4.69	4.90	6.50	4.67	4.92	5.73
P <sub>2</sub> O <sub>5</sub>	<0.03	<0.03	<0.03	0.02	<0.03	0.01	0.01	0.02	0.01	0.01	0.01
LOI b	0.14	0.22	0.26	0.43	0.72	0.76	0.60	0.94	0.39	0.45	0.71
Total	99.28	99.82	99.32	99.30	99.58	99.96	99.91	100.03	100.07	99.95	99.85

Mg# c	0.12	0.14	0.23	0.15	0.22	0.15	0.08	0.13	0.12	0.12	0.16
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Trace  
element  
(ppm)

Sc	5.07	5.19	4.79	11.2	5.07	2.97	2.57	3.32	2.67	2.96	3.07
V	6.67	3.99	6.01	10.5	6.75						
Cr	3.56	2.54	5.81	3.96	3.30	1.97	2.50	2.40	1.85	1.60	1.71
Co	0.47	0.29	0.47	1.54	0.97	0.57	0.54	0.76	0.64	0.55	0.62
Ni	0.93	0.72	2.69	1.23	0.77	1.59	1.66	2.24	1.77	1.31	1.69
Ga	20.5	17.3	16.9	17.0	15.6						
Rb	172	156	148	138	173	215	246	384	241	253	342
Sr	34.5	36.8	25.5	99.3	64.7	19.3	16.9	56.5	22.8	20.8	46.3
Y	35.1	23.9	25.3	35.0	32.3	51.5	50.4	50.2	51.9	52.0	54.2
Zr	197	242	205	257	97	318	306	296	327	323	329
Nb	26.208	18.162	20.772	21.112	22.824	72.700	75.400	63.800	71.500	80.100	78.000
Cs	3.686	1.111	2.342	4.678	6.764						
Ba	184.62	708.40	193.42	936.34	628.60	24.80	23.20	44.00	27.20	20.60	24.80
Hf	6.042	5.880	5.630	6.457	2.788	12.300	12.000	10.900	11.400	11.600	12.400
Ta	1.665	1.119	1.209	1.214	1.538	4.900	5.060	4.860	4.900	5.020	5.040
Pb	22.480	16.460	24.240	16.562	24.000	59.700	49.200	41.500	31.100	34.200	54.100
Th	23.580	17.830	20.100	17.380	17.418	27.800	26.600	25.800	26.600	27.100	27.500
U	4.508	2.494	3.814	2.668	2.826	5.640	6.020	5.620	7.170	7.560	5.410
La	27.00	39.80	37.54	57.33	34.06	70.70	66.00	67.30	69.50	69.30	71.10
Ce	59.56	80.76	77.32	115.20	67.46	137.00	138.00	139.00	140.00	141.00	142.00
Pr	7.13	8.87	8.56	12.64	7.43	16.30	15.40	15.70	15.80	15.90	16.40
Nd	27.04	31.14	30.38	45.16	26.54	60.00	56.40	58.10	58.40	58.80	60.60
Sm	6.45	5.57	5.56	8.50	5.57	13.20	12.30	12.40	12.80	12.80	13.80
Eu	0.26	0.55	0.27	1.54	0.61	0.08	0.07	0.10	0.08	0.08	0.11

Gd	6.21	4.74	4.82	7.66	5.31	12.30	11.80	11.90	12.00	11.70	12.30
Tb	0.97	0.69	0.71	1.08	0.84	1.87	1.85	1.79	1.80	1.80	1.88
Dy	5.85	4.05	4.24	6.17	5.19	10.40	9.82	9.79	9.54	9.82	10.40
Ho	1.20	0.81	0.87	1.23	1.08	1.90	1.86	1.85	1.85	1.85	1.95
Er	3.50	2.36	2.58	3.59	3.23	5.46	5.18	5.10	5.11	5.24	5.58
Tm	0.51	0.34	0.38	0.52	0.48	0.81	0.78	0.78	0.74	0.81	0.82
Yb	3.39	2.25	2.56	3.47	3.23	4.74	4.84	4.81	4.51	4.76	5.05
Lu	0.50	0.34	0.38	0.52	0.48	0.72	0.70	0.67	0.69	0.69	0.75
(La/Yb) N d	5.71	12.70	10.51	11.84	7.55	6.58	6.91	7.18	6.54	6.90	6.73
Eu/Eu* e	0.12	0.33	0.16	0.58	0.35	0.02	0.02	0.03	0.02	0.02	0.03
Sr/Sr* e	0.07	0.06	0.05	0.12	0.13	0.02	0.02	0.05	0.02	0.02	0.04

a. Fe<sub>2</sub>O<sub>3</sub> is total Fe expressed as Fe<sup>3+</sup>.

b. LOI (Loss On Ignition) is conformed to the equation:  $LOI = (M_{before} - M_{after}) / M_{before} \times 100\%$  in which  $M_{after}$  represents for the mass reweighed after heating at 1000°C in the furnace for several hours and  $M_{before}$  is the initial mass about 0.5g.

c. Mg# = molar Mg/[Mg+Fe<sup>2+</sup>] with 10% total Fe as Fe<sup>3+</sup>.

d. Subscript N stands for normalised values against Chondrite.

e.  $Eu/Eu^* = Eu_{PM} / [Sm_{PM} * Gd_{PM}]^{1/2}$ ,  $Sr/Sr^* = Sr_{PM} / [Pr_{PM} * Nd_{PM}]^{1/2}$ , where subscript PM denotes normalised values against Primary Mantle.

**Table 4**

Whole rock Sr-Nd isotopic composition of the late Triassic mafic dikes and felsic volcanic rocks from the East Kunlun Orogenic Belt.

Sample	Rb		Sr		87Rb/8		87Sr/8		±2		Sm		Nd		t	
	(pp m)	(pp m)	(pp m)	(pp m)	6Sr	6Sr	σ	Isr	(pp m)	(pp m)	147Sm/14	143Nd/14	±2	143Nd/144	εNd (M	(t) a)
YNG12-01	140.3	531.4	0.76	0.7101	37	10	66	0.7077	5.71	4	0.1154	0.512397	5	0.512232	-2.4	4 218
YNG12-03	599.4	2	0.20	0.7076	22	4	17	0.7070	6.11	4	0.1147	0.512409	8	0.512246	-2.1	8 218
YNG12-05	134.7	694.6	0.56	—	—	—	—	—	6.73	2	0.1098	0.512381	3	0.512225	-2.5	9 218
YNG12-08	172.3	512.8	0.97	0.7102	02	16	85	0.7071	7.20	4	0.1126	0.512395	6	0.512234	-2.4	0 218
QMX12-11	456.88.0	4	0.56	0.7103	96	4	49	0.7086	5.58	0	0.1084	0.512333	2	0.512177	-3.4	6 220
QMX12-01	211.154.	9	3.96	0.7212	67	4	92	0.7088	3.68	6	0.1180	0.512329	4	0.512159	-3.8	3 220
QMX12-08	174.119.	9	4.21	0.7229	26	5	41	0.7097	3.45	0	0.1023	0.512305	3	0.512157	-3.8	5 220
YDE12-02	159.104.	7	4.40	0.7231	18	5	52	0.7088	4.85	4	0.1217	0.512284	5	0.512102	-4.7	3 228
RSX12-48	171.7	34.5	14.41	0.7550	49	4	16	0.7083	6.45	4	0.1452	0.512300	4	0.512083	-5.0	9 228
DL09-01*	215.0	19.3	32.53	0.8348	90	9	54	0.7363	13.2	60.0	0.1330	0.512397	5	0.512212	-2.9	7 213
DL09-03*	384.0	56.5	19.78	0.7647	00	8	99	0.7047	12.4	58.1	0.1290	0.512392	4	0.512212	-2.9	6 213
DL09-05*	253.0	20.8	35.54	0.8417	00	9	31	0.7340	12.8	58.8	0.1316	0.512391	10	0.512208	-3.0	5 213
DL09-06*	342.0	46.3	21.44	0.7720	00	4	64	0.7070	13.8	60.6	0.1377	0.512399	4	0.512207	-3.0	6 213

$Isr = [(87Sr/86Sr) - (87Rb/86Sr)(e^{\lambda t} - 1)]$ ;  $143Nd/144Ndi = [(143Nd/144Nd) - (147Sm/144Nd)(e^{\lambda t} - 1)]$ ;

$\epsilon Nd(t) = [(143Nd/144Ndi) / (143Nd/144Nd_{CHUR}) - 1] \times 104$ .

$147Sm/144Nd_{CHUR} = 0.1967$ ;  $143Nd/144Nd_{CHUR} = 0.512638$ ;  $\lambda(87Rb) = 1.42 \times 10^{-11} \text{ yr}^{-1}$ ;

$\lambda(147Sm) = 6.54 \times 10^{-12} \text{ yr}^{-1}$ .

— Not detected.

\*Data come from Ding et al. (2011).

**Table 5**

Whole rock Hf isotopic composition of the late Triassic mafic dikes and felsic volcanic rocks from the East Kunlun Orogenic Belt.

Sample	Lu (ppm)	Hf (ppm)	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf} \pm 2\sigma$	$^{176}\text{Hf}/^{177}\text{Hf}_i$	$\epsilon\text{Hf}(t)$	t (Ma)
YNG12-01	0.274	5.345	0.0073	0.282680	4	0.282677	-2.85 218
YNG12-03	0.281	5.040	0.0079	0.282665	3	0.282662	-3.39 218
YNG12-05	0.290	6.138	0.0067	0.282650	3	0.282647	-3.92 218
YNG12-08	0.303	6.661	0.0065	0.282669	6	0.282666	-3.24 218
QMX12-11	0.254	5.900	0.0061	0.282630	2	0.282628	-4.59 220
QMX12-01	0.363	6.252	0.0082	0.282663	2	0.282659	-3.48 220
QMX12-08	0.270	3.552	0.0108	0.282676	4	0.282671	-3.06 220
YDE12-02	0.525	3.702	0.0201	0.282675	4	0.282666	-3.24 228
RSX12-48	0.497	6.042	0.0117	0.282654	3	0.282649	-3.83 228
DL09-01	0.720	12.300	0.0083	0.282702	2	0.282698	-2.12 213*
DL09-03	0.670	10.900	0.0087	0.282689	2	0.282685	-2.59 213*

$^{176}\text{Hf}/^{177}\text{Hf}_i = [(^{176}\text{Hf}/^{177}\text{Hf}) - (^{176}\text{Lu}/^{177}\text{Hf})(e^{\lambda t} - 1)]$ ;

$\epsilon\text{Hf}(t) = [(^{176}\text{Hf}/^{177}\text{Hf}_i) / (^{176}\text{Hf}/^{177}\text{Hf}_{\text{CHUR}}) - 1] \times 10^4$ .

$^{176}\text{Lu}/^{177}\text{Hf}_{\text{CHUR}} = 0.0332$ ;  $^{176}\text{Hf}/^{177}\text{Hf}_{\text{CHUR}} = 0.282772$ ;  $\lambda(^{176}\text{Lu}) = 1.865 \times 10^{-11} \text{yr}^{-1}$ .

\*Age data come from Ding et al. (2011).



**Table 6**

Whole rock Pb isotopic composition of the late Triassic mafic dikes from the East Kunlun Orogenic Belt.

Sample	U (pp m)	Th (pp m)	Pb (pp m)	208Pb/20 4Pb	$\pm 2$ $\sigma$	207Pb/20 4Pb	$\pm 2$ $\sigma$	206Pb/20 4Pb	$\pm 2$ $\sigma$	208Pb/20 4Pbi	207Pb/20 4Pbi	206Pb/20 4Pbi	t (Ma)
YNG12	1.51	4.79	10.7										
-01	0	6	66	38.801	24	15.646	11	18.825	12	67.215	15.631	18.825	218
YNG12	1.01	4.16	11.2										
-03	7	4	54	38.803	27	15.651	13	18.801	14	62.403	15.641	18.801	218
YNG12	1.42	5.95	16.8										
-05	8	2	58	38.777	18	15.644	6	18.789	7	61.297	15.635	18.789	218
YNG12	2.44	5.81	12.6										
-08	8	0	20	38.841	50	15.648	17	18.850	9	68.205	15.627	18.850	218

$208\text{Pb}/204\text{Pbi}=[(208\text{Pb}/204\text{Pb})-(232\text{Th}/204\text{Pb})(e^{\lambda t}-1)]$ ;

$207\text{Pb}/204\text{Pbi}=[(207\text{Pb}/204\text{Pb})-(235\text{U}/204\text{Pb})(e^{\lambda t}-1)]$ ;

$206\text{Pb}/204\text{Pbi}=[(206\text{Pb}/204\text{Pb})-(238\text{U}/204\text{Pb})(e^{\lambda t}-1)]$ .

$\lambda(232\text{Th})=4.95\times 10^{-11}\text{yr}^{-1}$ ;  $\lambda(235\text{U})=9.85\times 10^{-10}\text{yr}^{-1}$ ;  $\lambda(238\text{U})=1.55\times 10^{-10}\text{yr}^{-1}$ .

**Highlights**

1. The (sub-) volcanic rocks from the East Kunlun Orogenic Belt formed at late Triassic.
2. Mafic dikes are derived from the metasomatized subcontinental lithospheric mantle.
3. Felsic volcanic rocks evolved from melts of juvenile crustal materials.
4. The (sub-) volcanic rocks are associated with post-collisional extension.